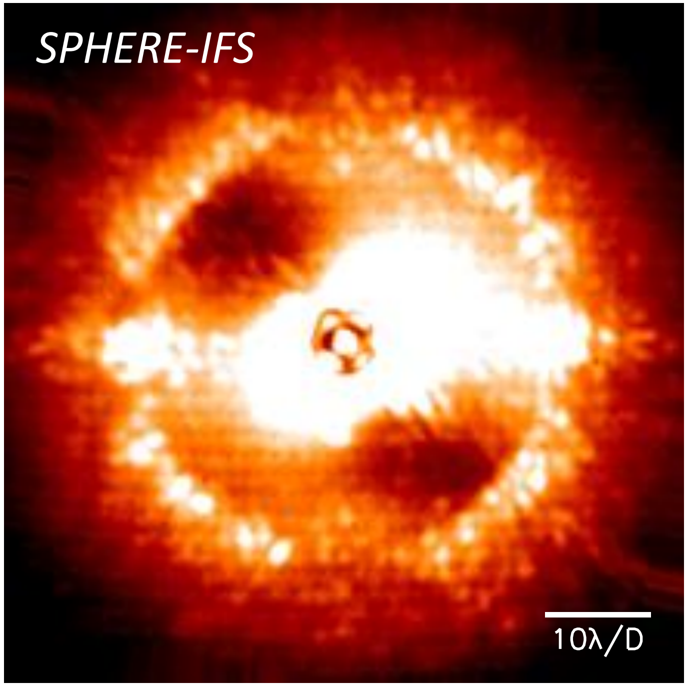
Peering through SPHERE high contrast images

Faustine Cantalloube (MPIA)

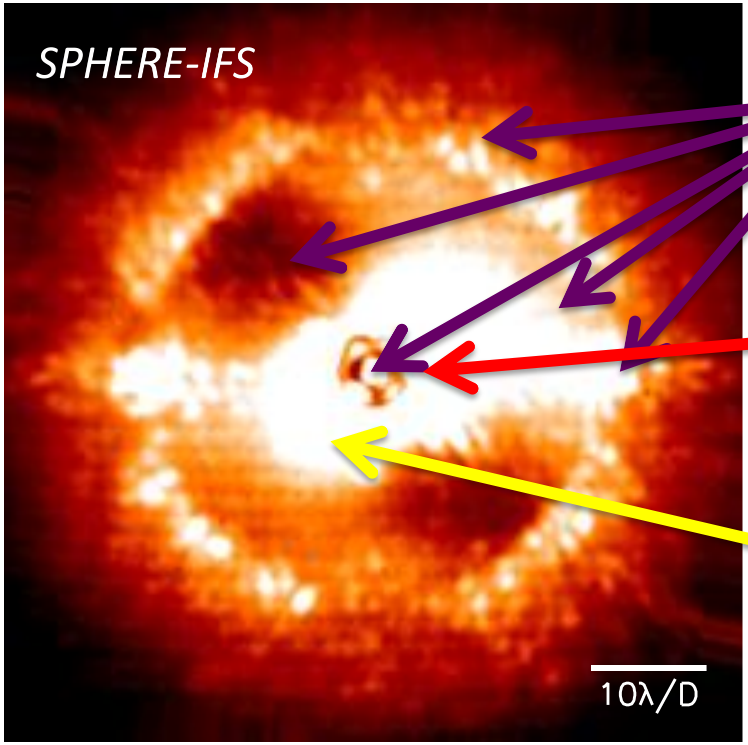
SPHERE
Spectro-Polarimetric
High-contrast
Exoplanet REsearch



AstroTechTalk
9th November 2018

Peering through SPHERE high contrast images

0- High contrast imaging: why, how and who



1- Dissection of a SPHERE image

2- The wind driven halo

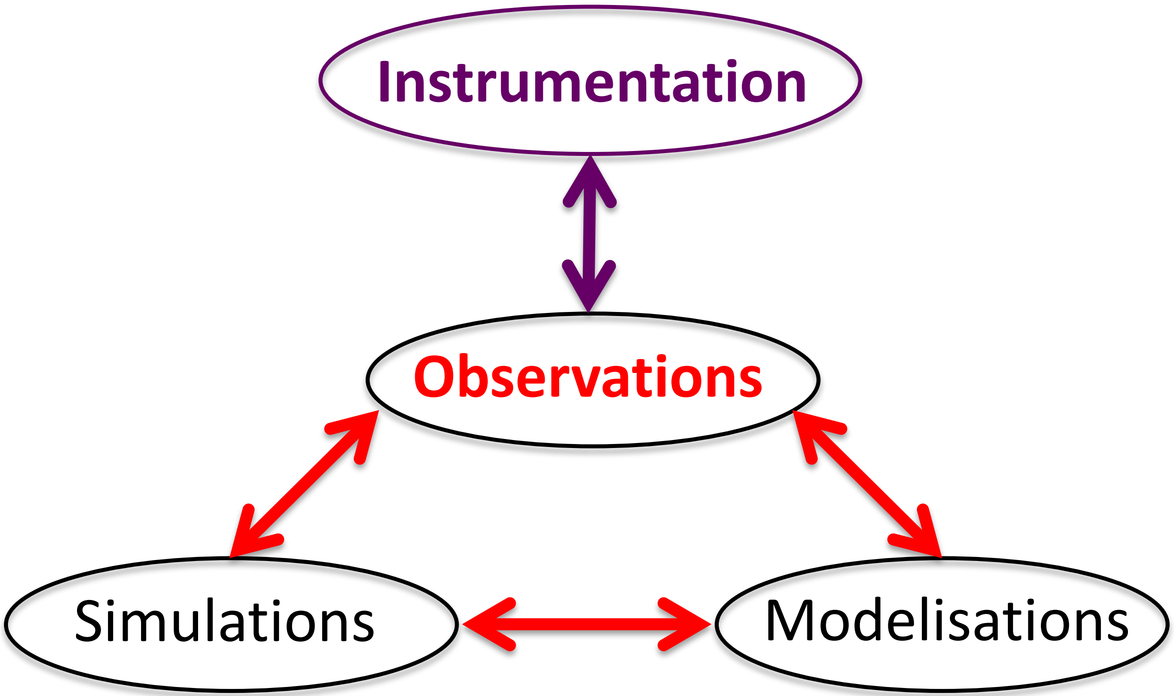
3- The assymmetry of the wind driven halo

4- Extrapolation to ELT…

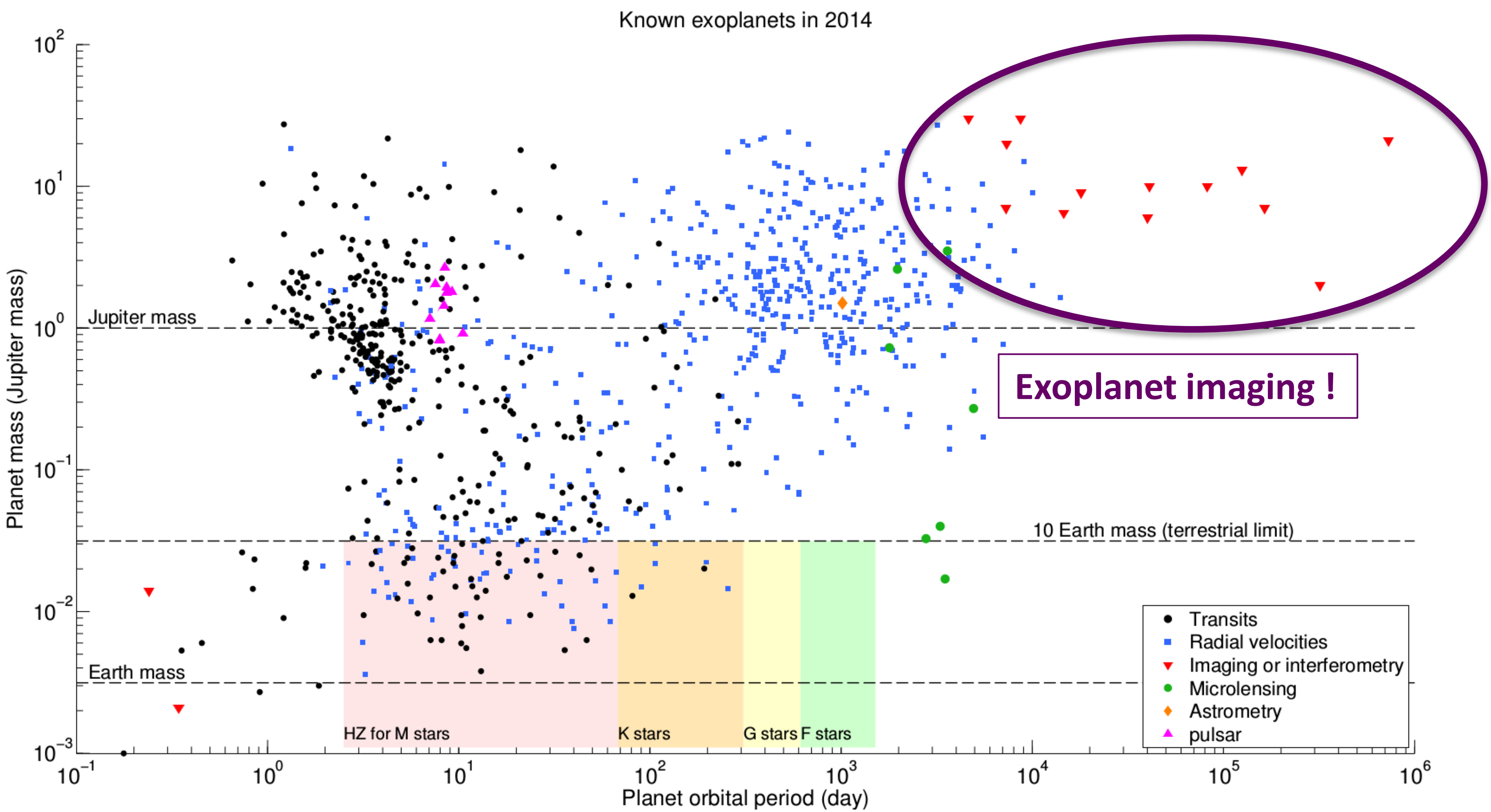
The 3 questions about exoplanets

- Planetary **formation**
- **Nature** of exoplanets
- **Dynamical** and **physical evolution** of exoplanets

To address this astronomers have three main pathways:

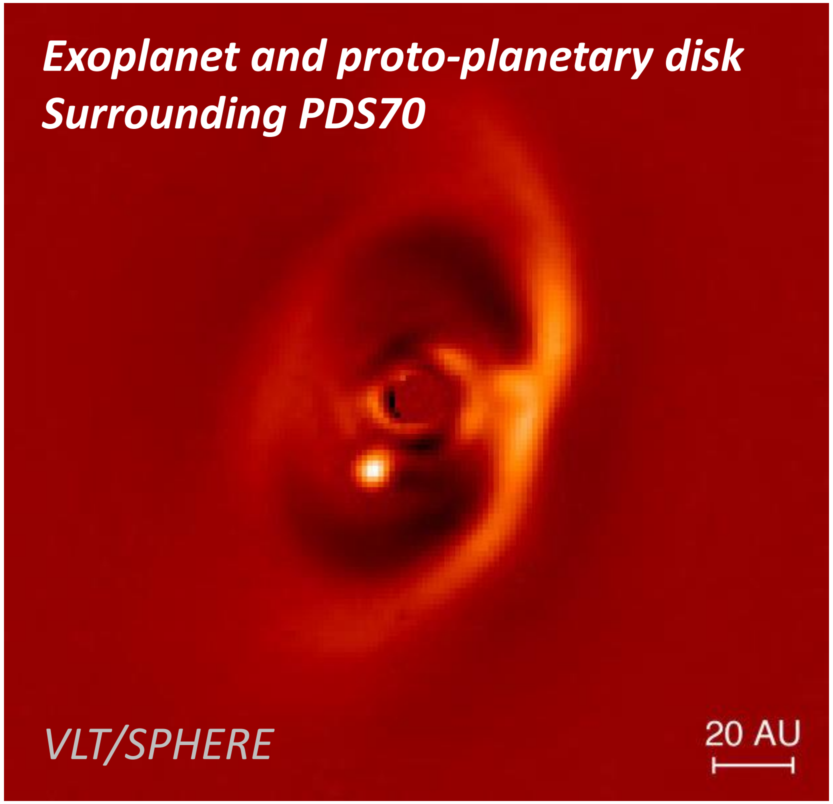


Why do we do HCI for exoplanets ?



- **Complementary** to other techniques: young stars, massive and distant planets
- Direct extraction of **spectrum:** atmospheric composition and structures
- Planetary system **architecture:** planet-planet or planet-disk interactions, follow-up…

Why do we get with HCI ?



Three observables:

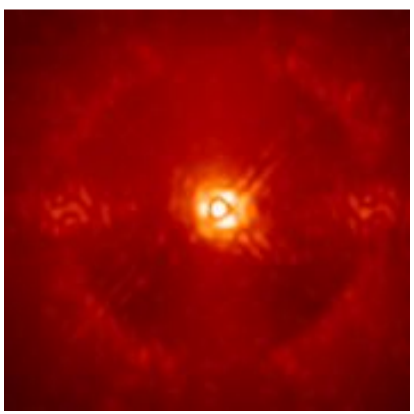
- Projected **separation** from the host star,
- **Contrast** to the host star,
- **Detection limit** for the data set

Why do we really get with HCI ?

<u>**From the three observables:**</u>

- **Planet parameters:** Mass, radius, temperature, physical distance…
- **Dynamical models:** orbital parameters, migration, scaterring
- **Evolutionary model:** clouds, dust, atmosphere compounds…
- **Statistical survey:** type of companions, link to host star, environment…

-> discriminate between different planetary **formation** and **evolution** models



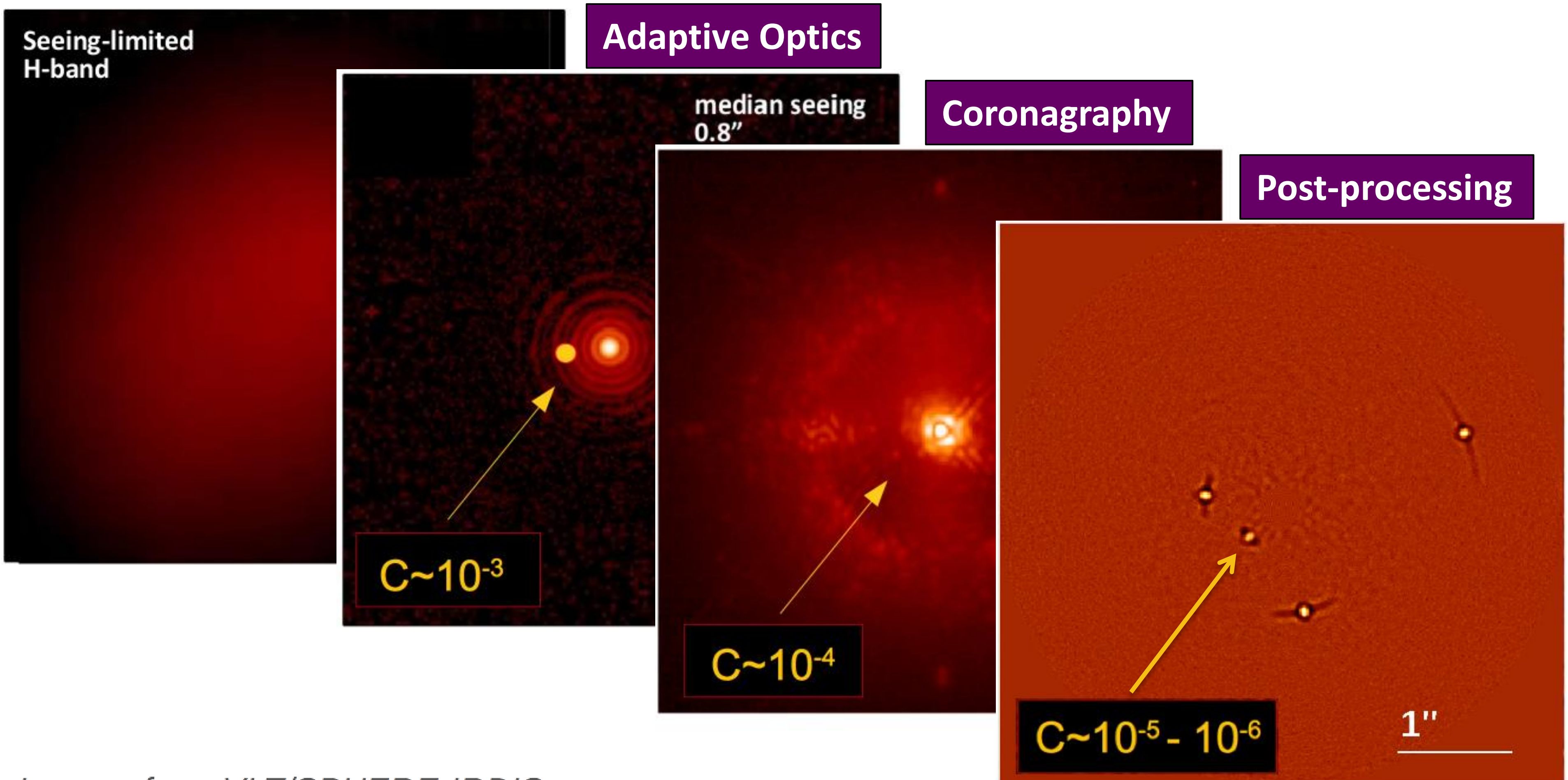
Raw image from
VLT/SPHERE/IFS

Loads of work…

Artistic view
of an exoplanetary system

The three pillars of HCI !

Today reaching contrast of **10^{-6}** contrast at **500 mas**, in infrared

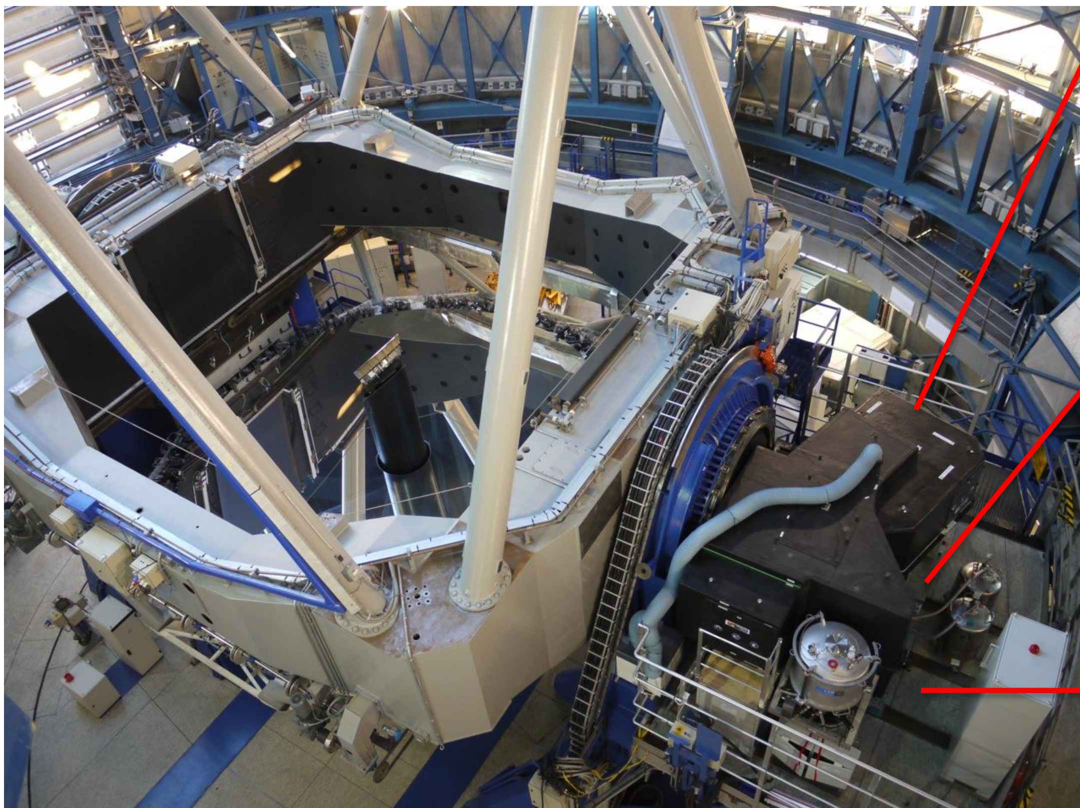


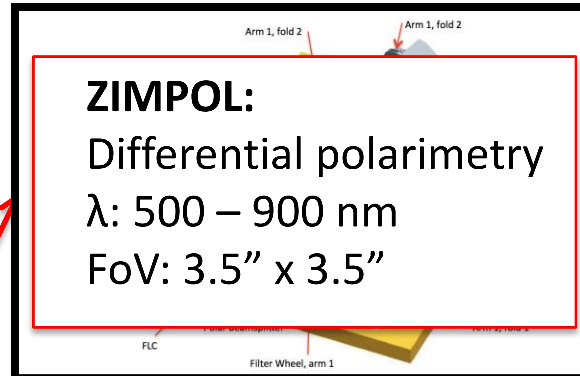
Images from VLT/SPHERE-IRDIS:
HR8799 in H-band (1.6µm)

The SPHERE instrument dedicated to HCI

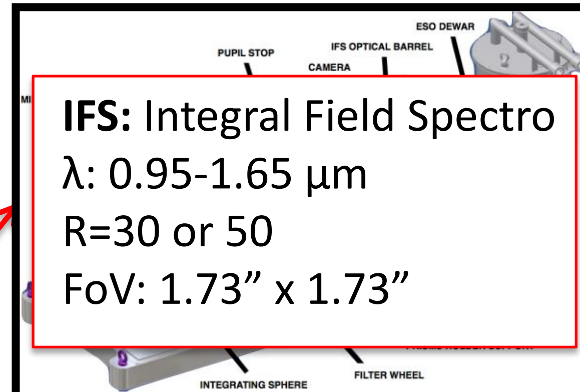
Commissioned in May 2014

- One common path instrument
- Three subsystem instruments

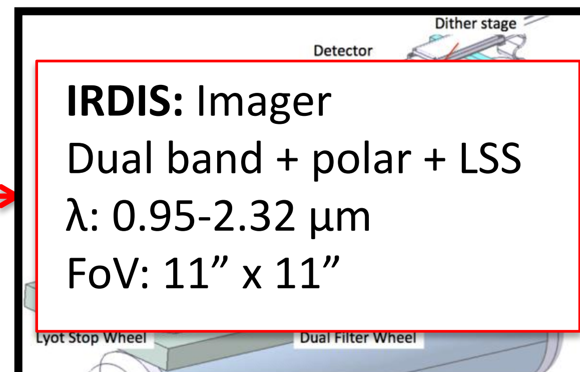




ZIMPOL:
Differential polarimetry
λ: 500 – 900 nm
FoV: 3.5” x 3.5”

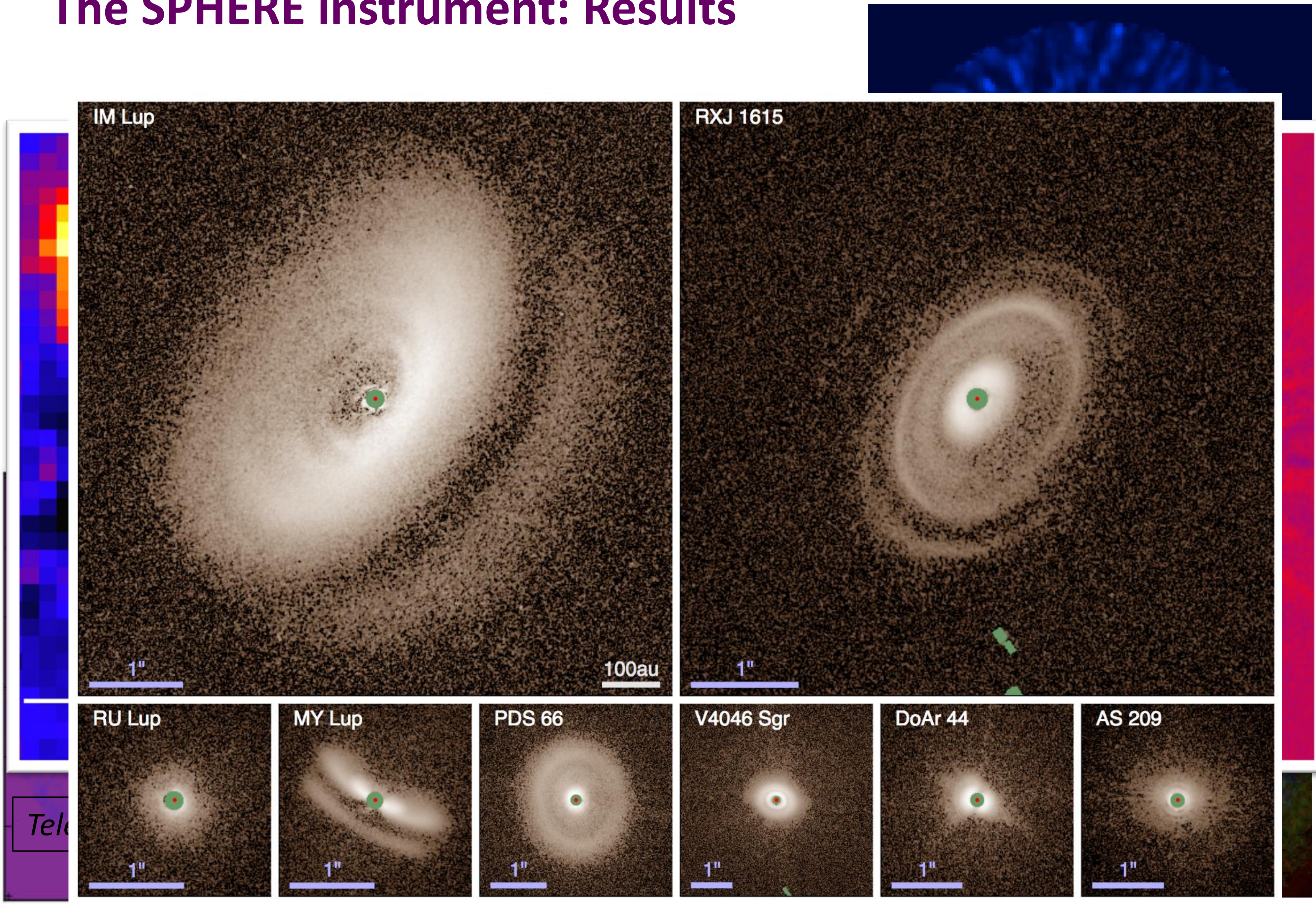


IFS: Integral Field Spectro
λ: 0.95-1.65 μm
R=30 or 50
FoV: 1.73” x 1.73”



IRDIS: Imager
Dual band + polar + LSS
λ: 0.95-2.32 μm
FoV: 11” x 11”

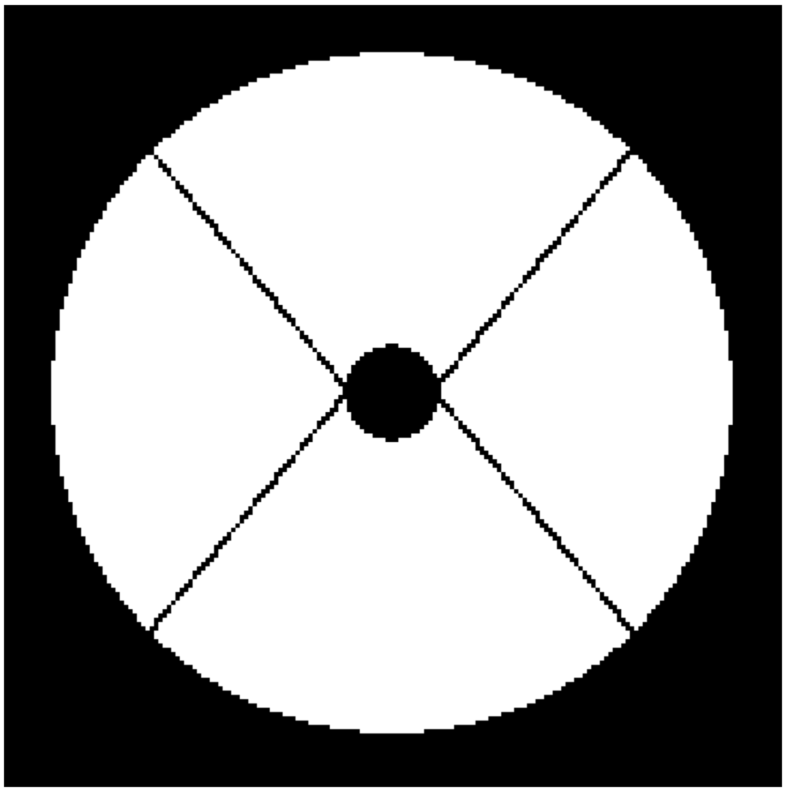
The SPHERE instrument: Results



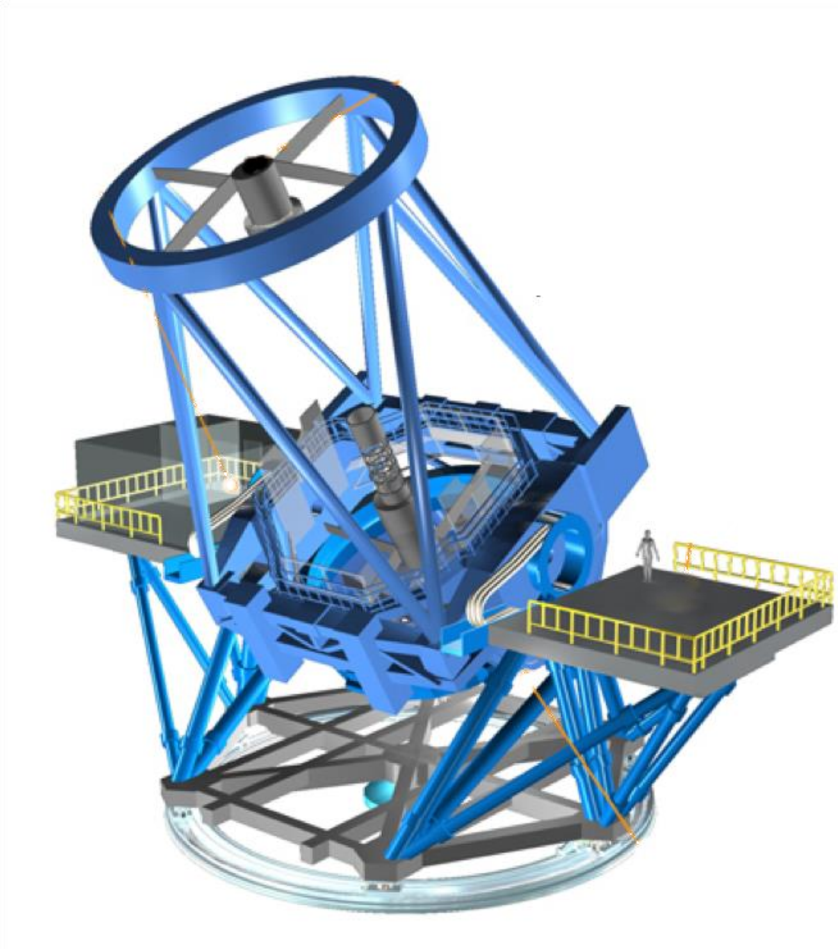
Images from SPHERE

Features presented after are from:

1- Telescope itself



Diameter of the pupil (7.99 m)



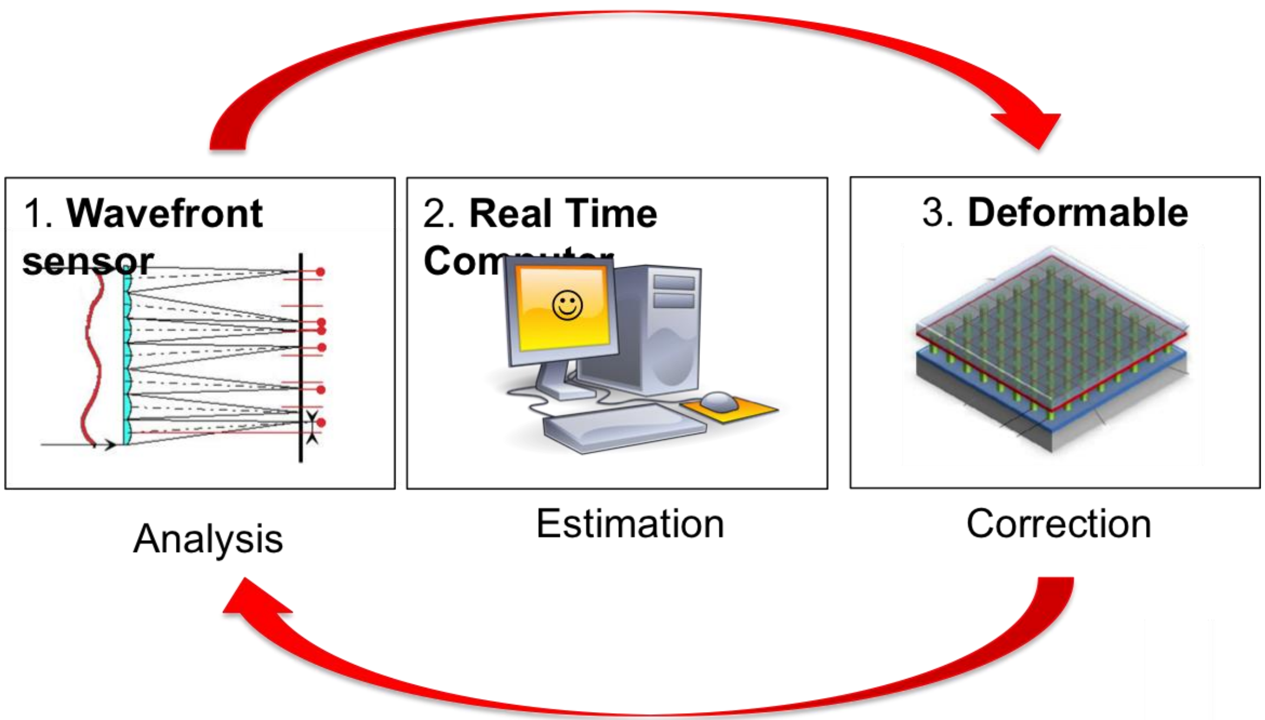
Subaru telescope, NAOJ, Hawaï, USA

Images from SPHERE

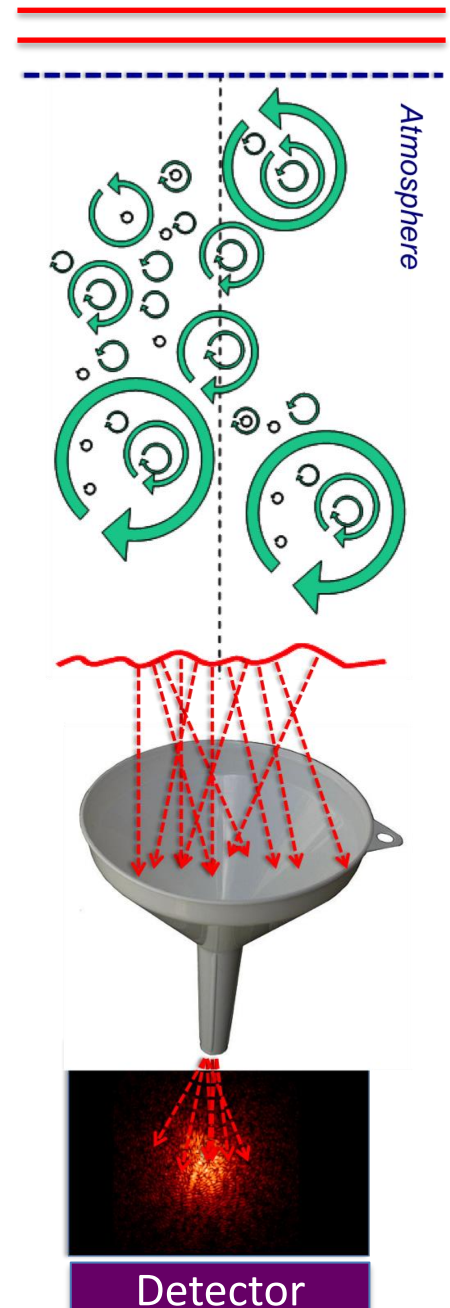
Features presented after are from:

1- Telescope itself

2- Adaptive Optics (AO) residuals



Closed loop !



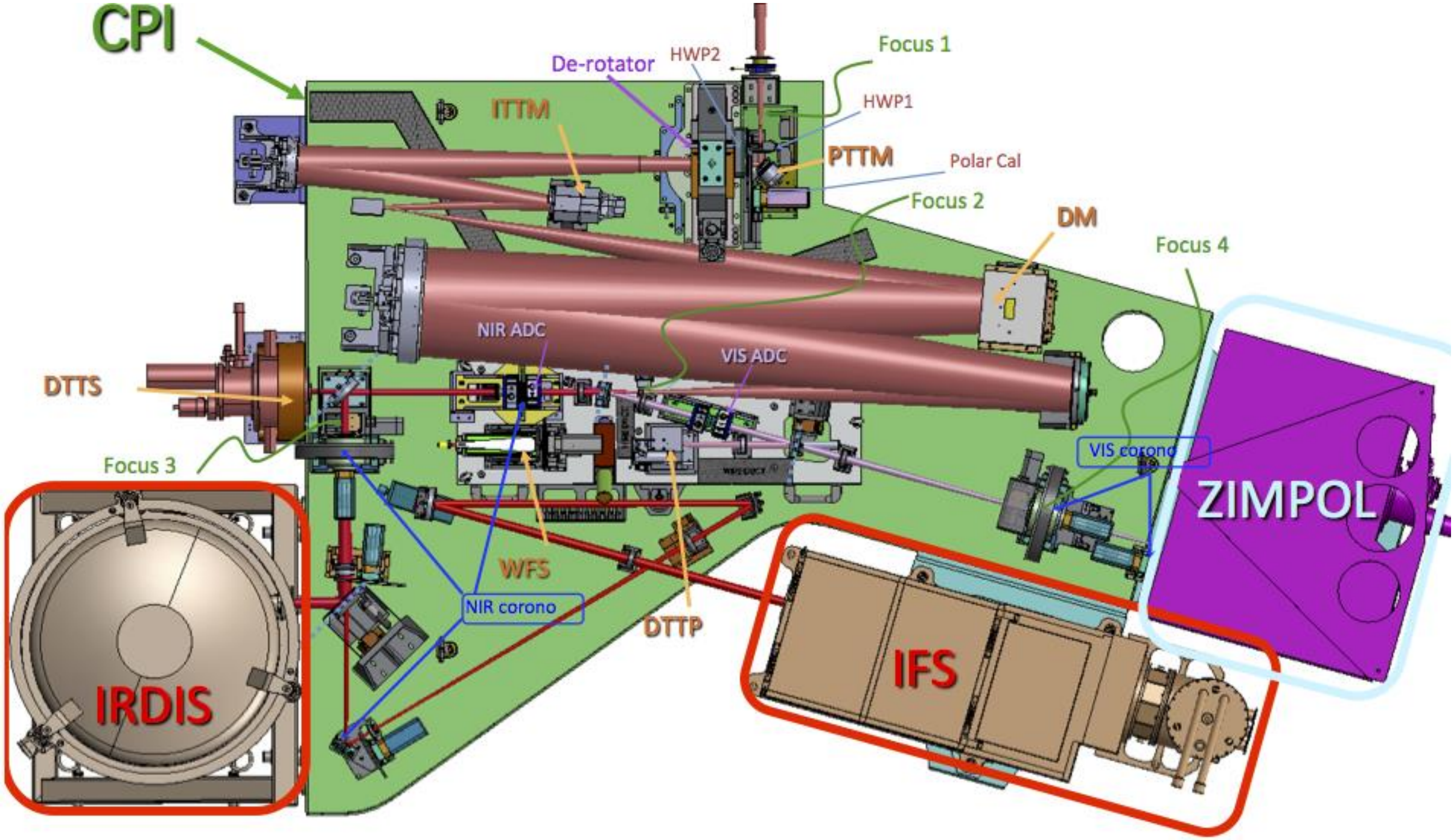
Images from SPHERE

Features presented after are from:

1- Telescope itself

2- AO residuals

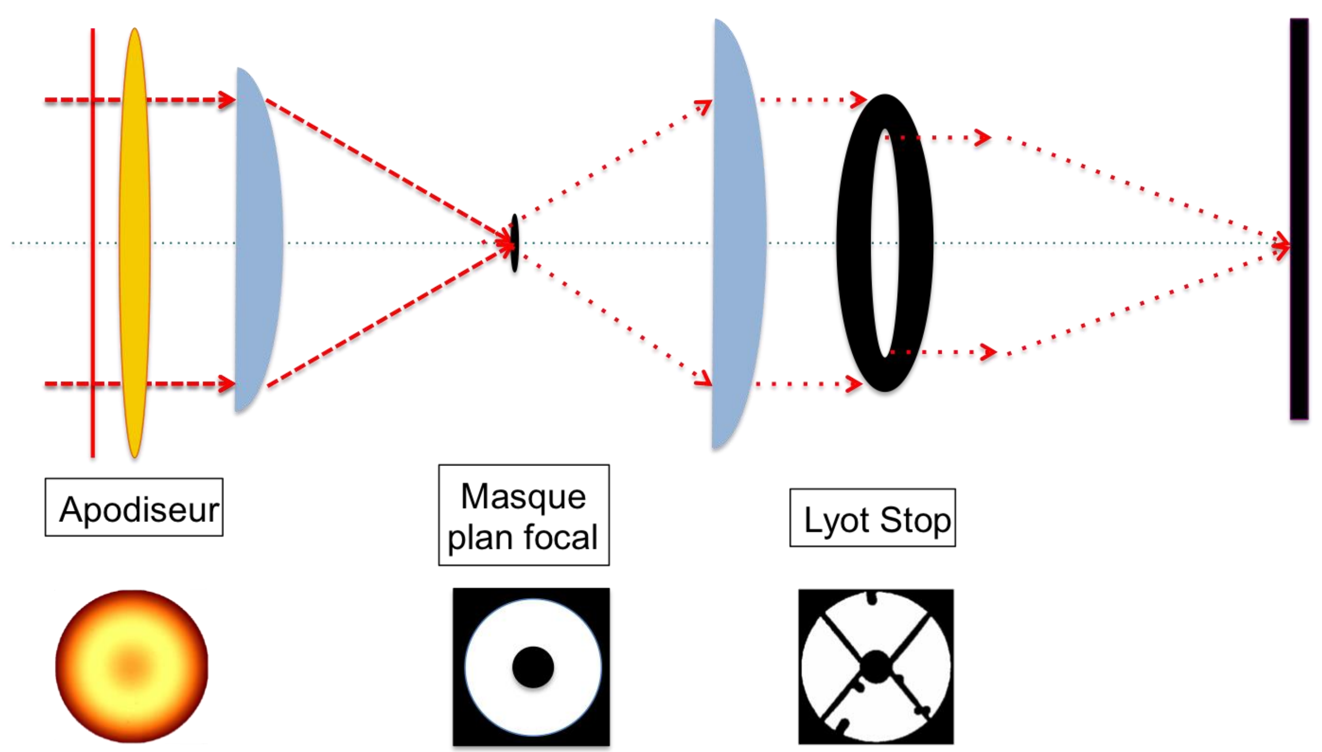
3- Instrument itself



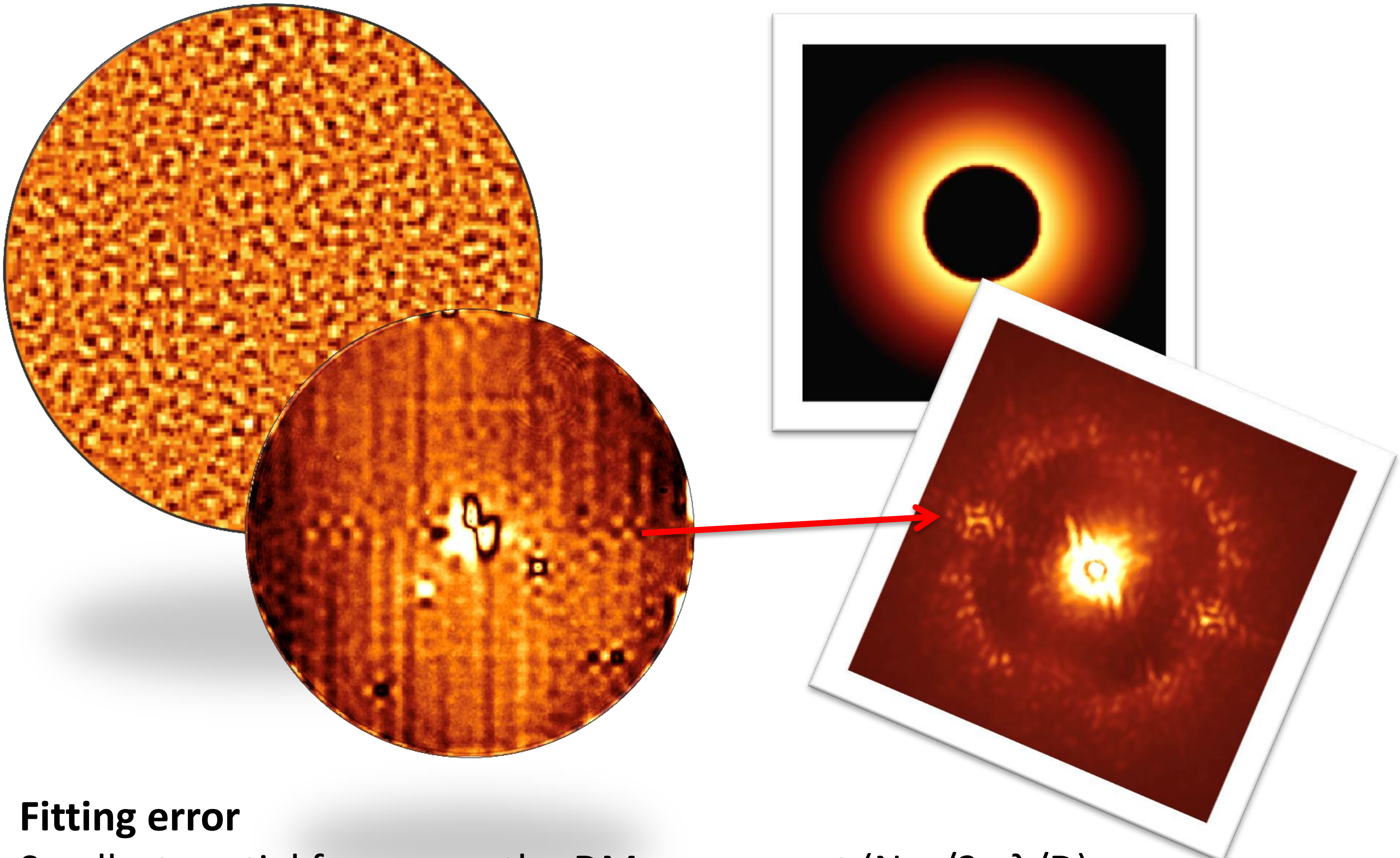
Images from SPHERE

Features presented after are from:

1- Telescope itself
2- AO residuals
3- Instrument itself
4- Coronagraph concept: Apodized Lyot Coronagraph



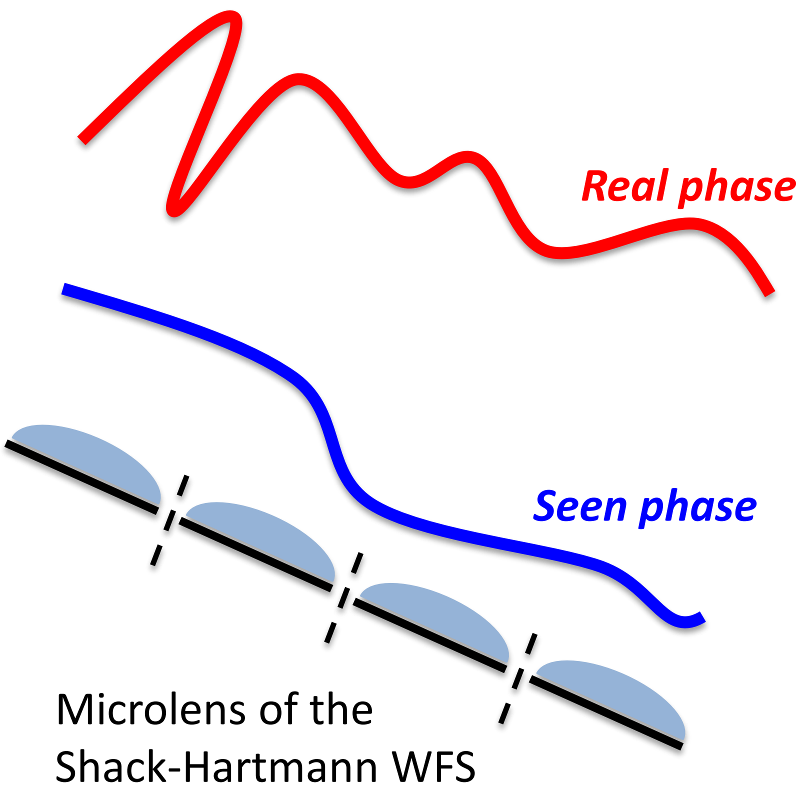
Correction radius at 20 λ/D

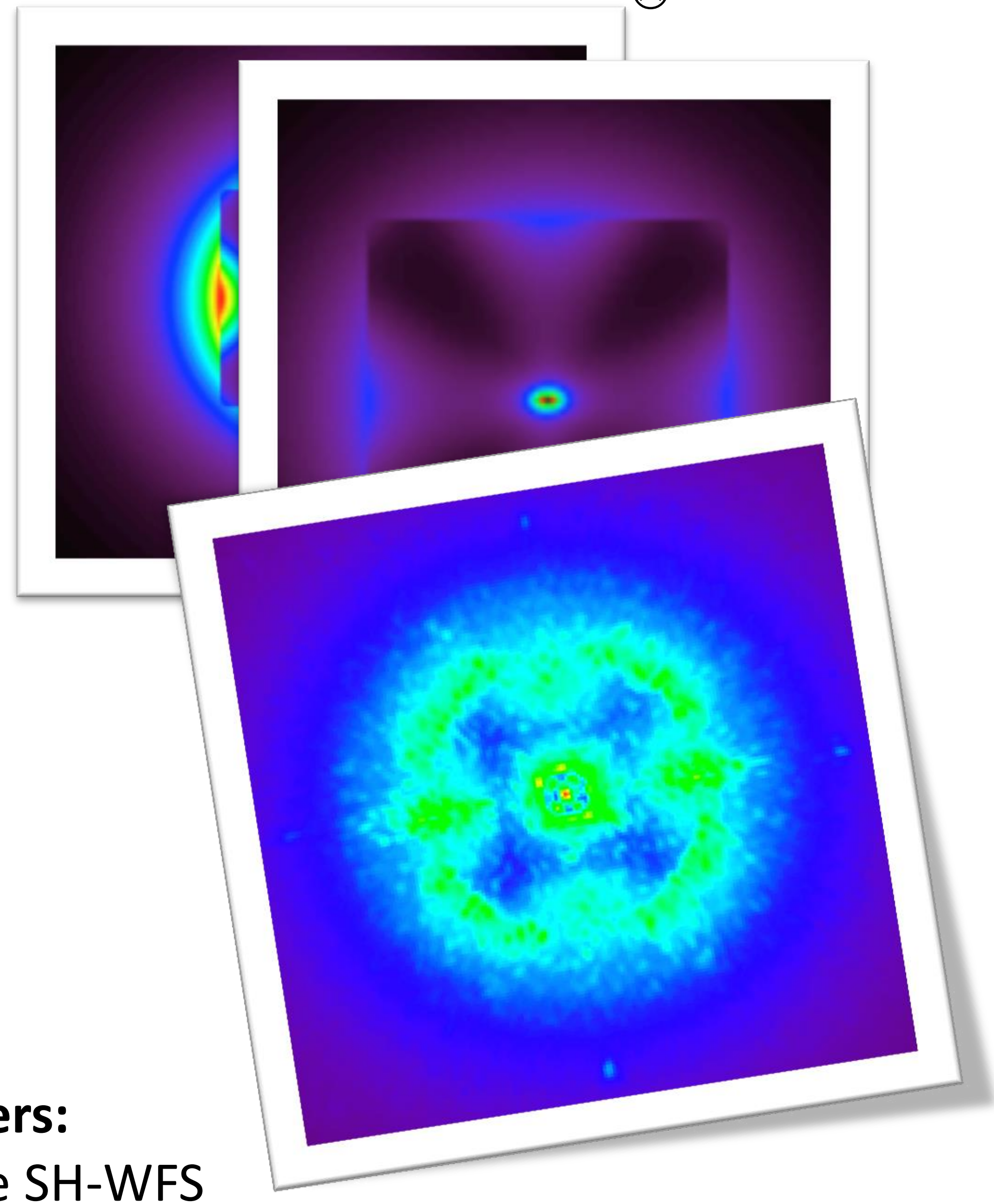


Fitting error

Smallest spatial frequency the DM can correct ($N_{act}/2 . \lambda/D$)

Aliasing features

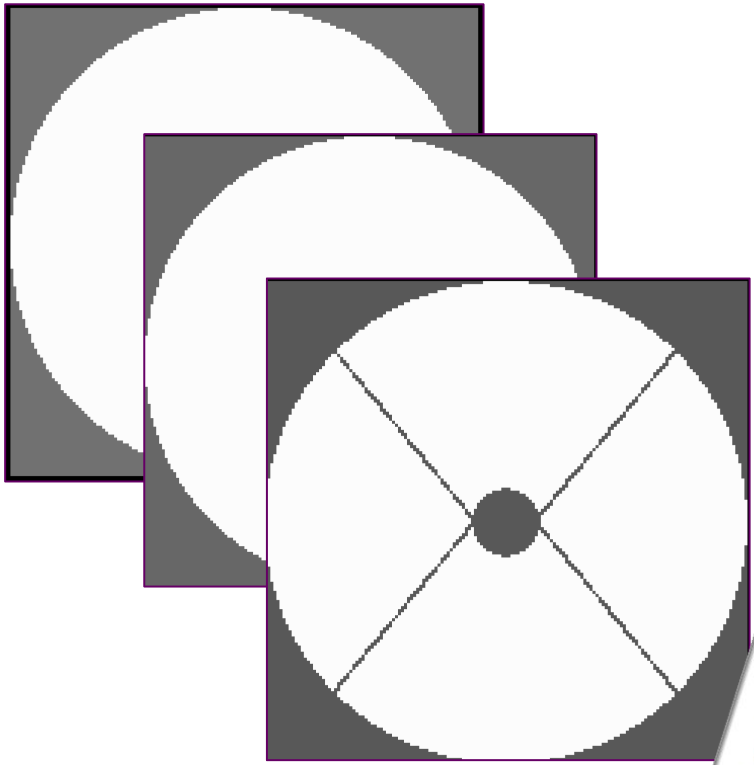


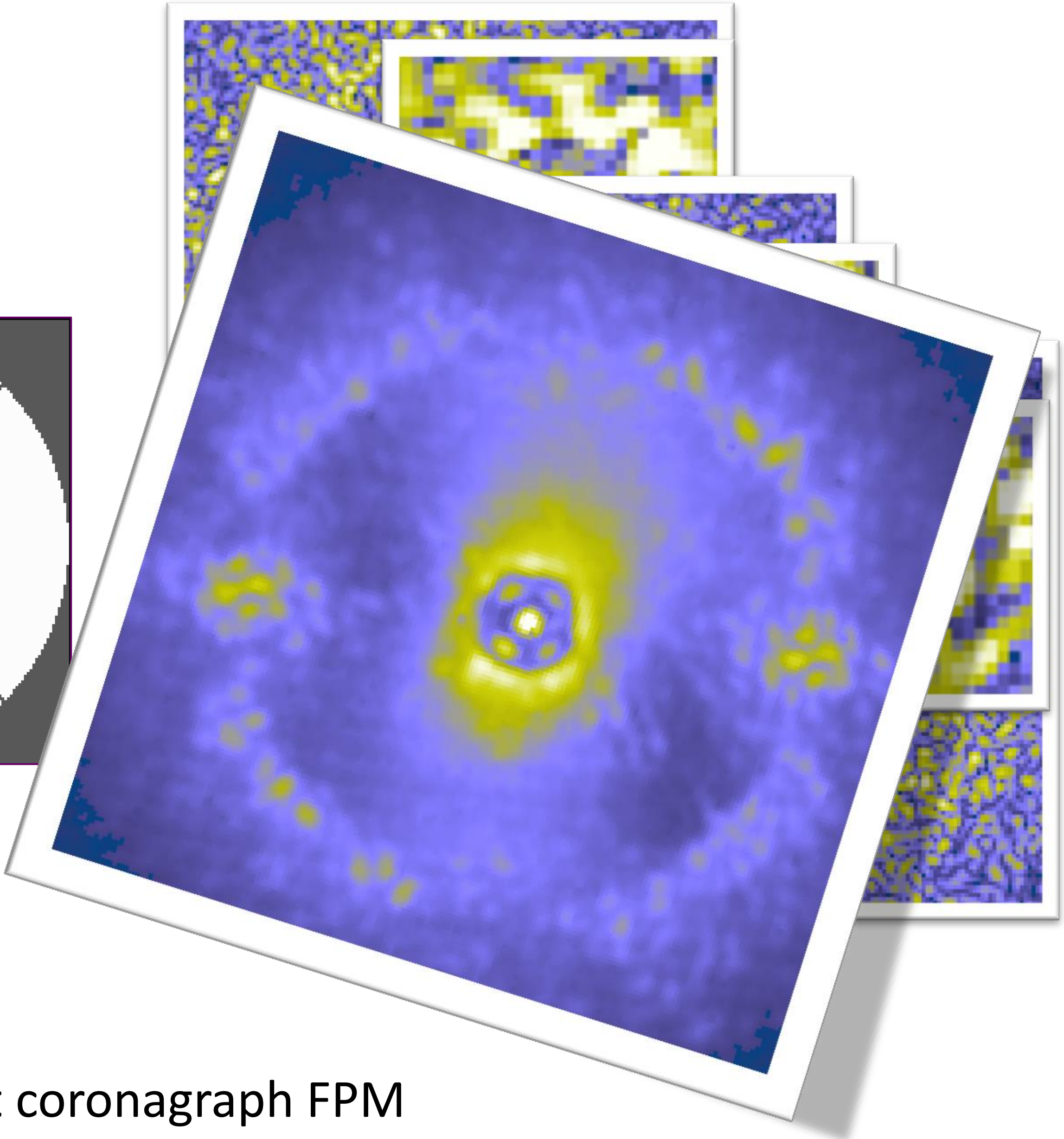


High orders are 'seen as' low orders:

Use of a spatial filter upstream the SH-WFS

Coronagraphic signature

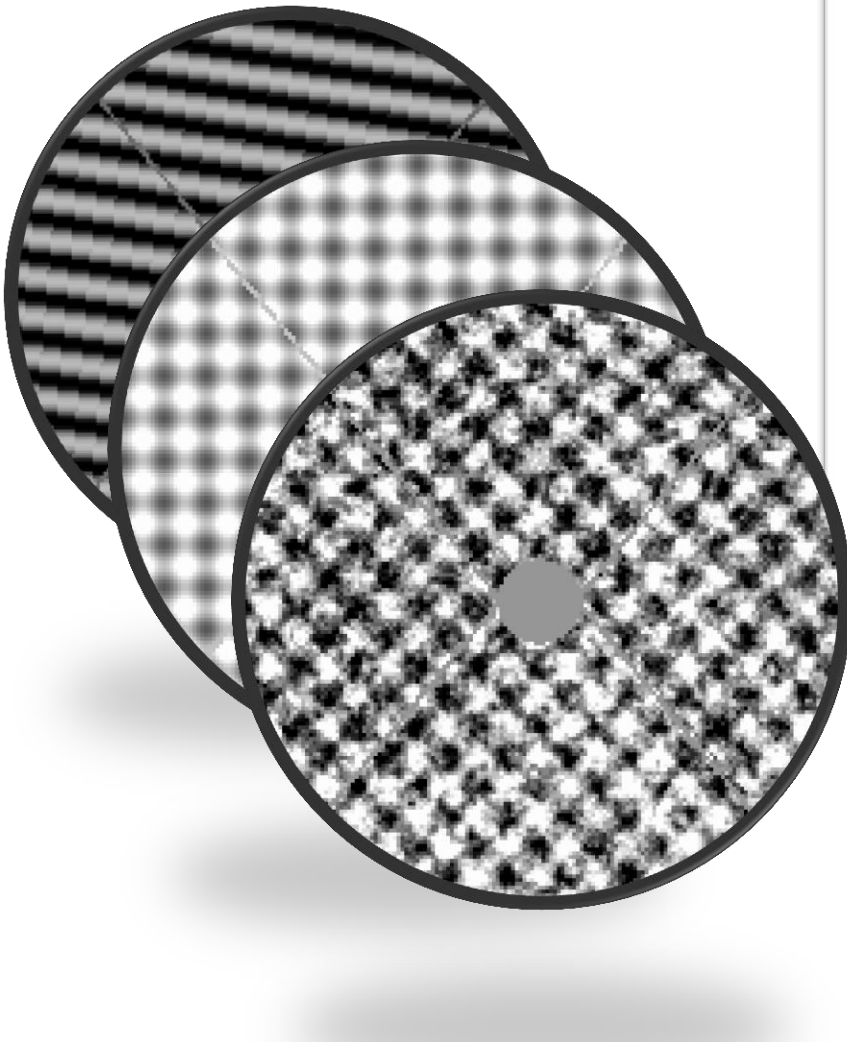


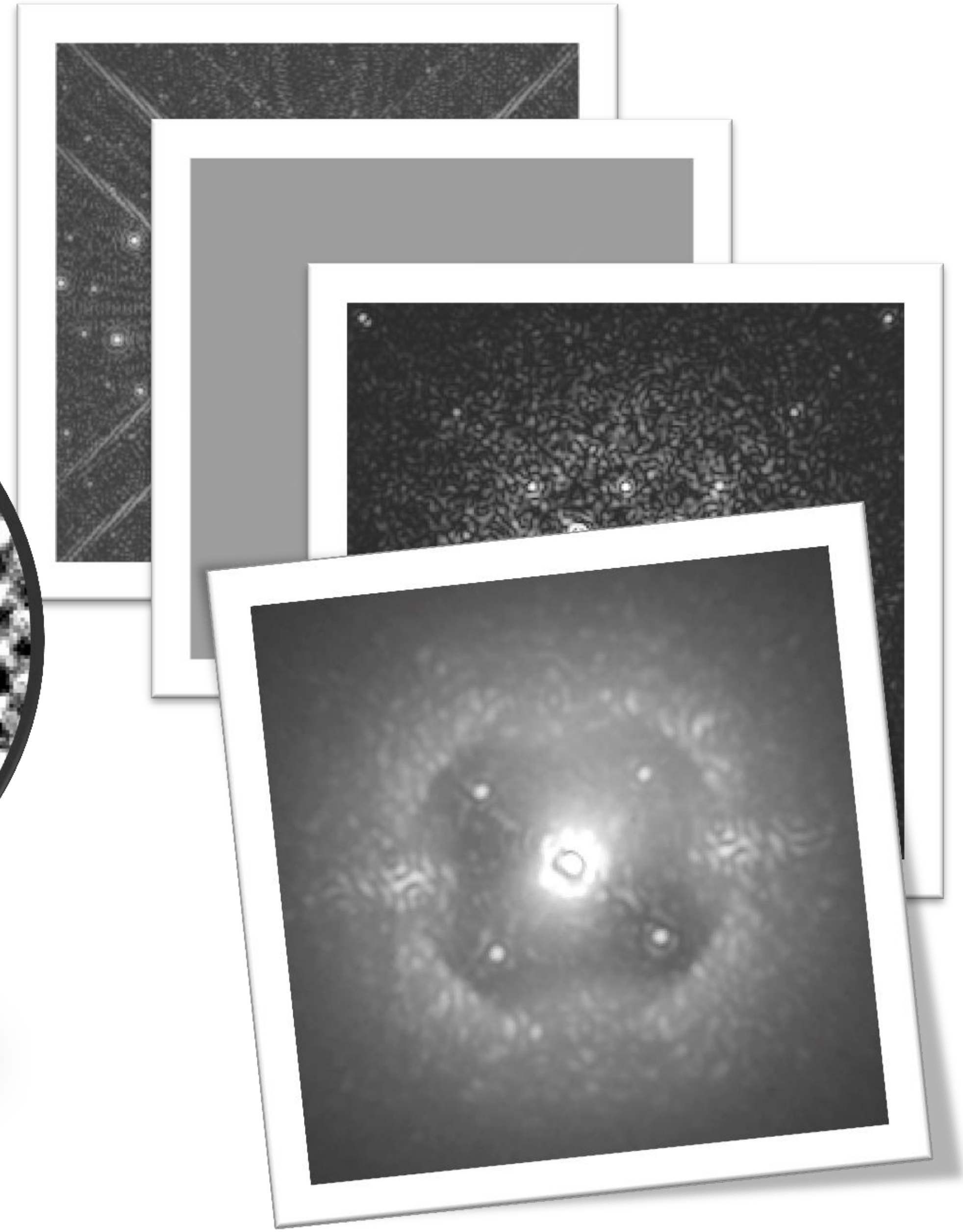


Poisson spot (or Arago spot)

Due to diffraction by the Lyot coronagraph FPM

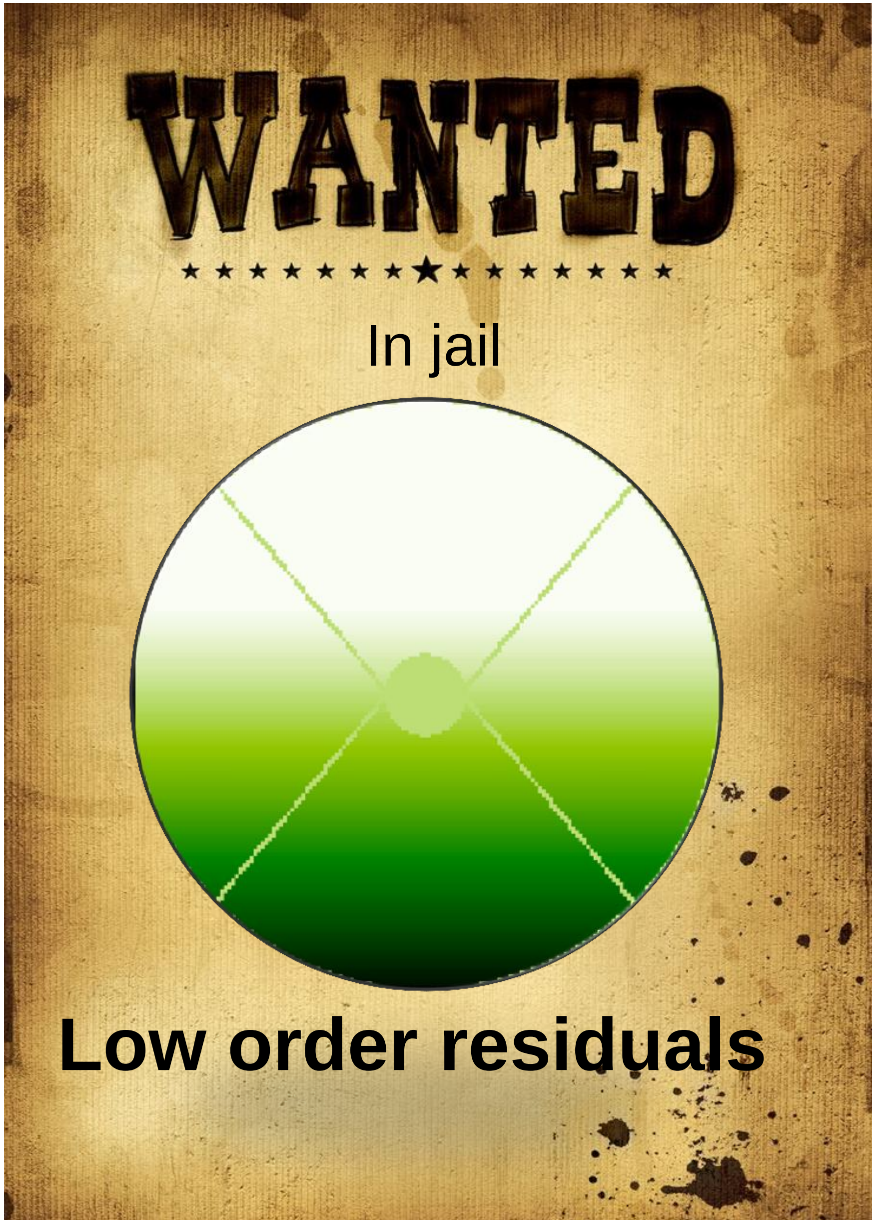
Satellite spots



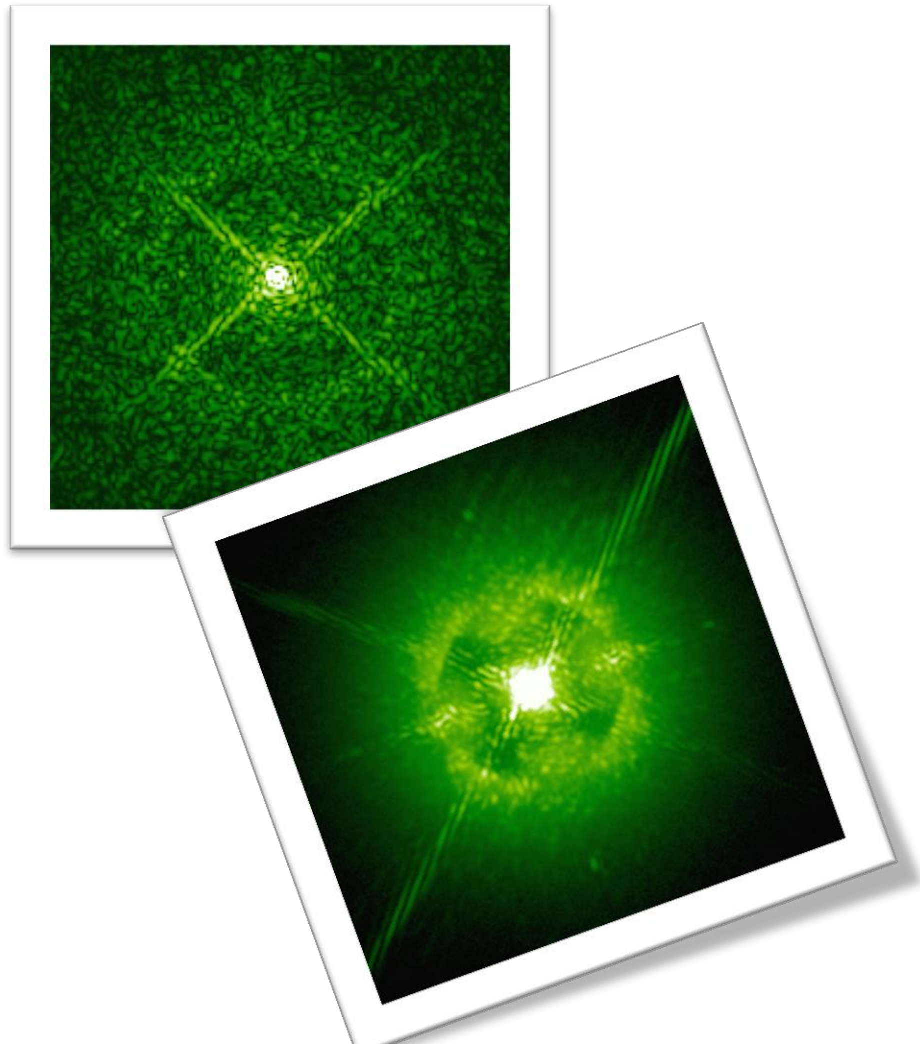


Waffle pattern on DM:
Note the second orders

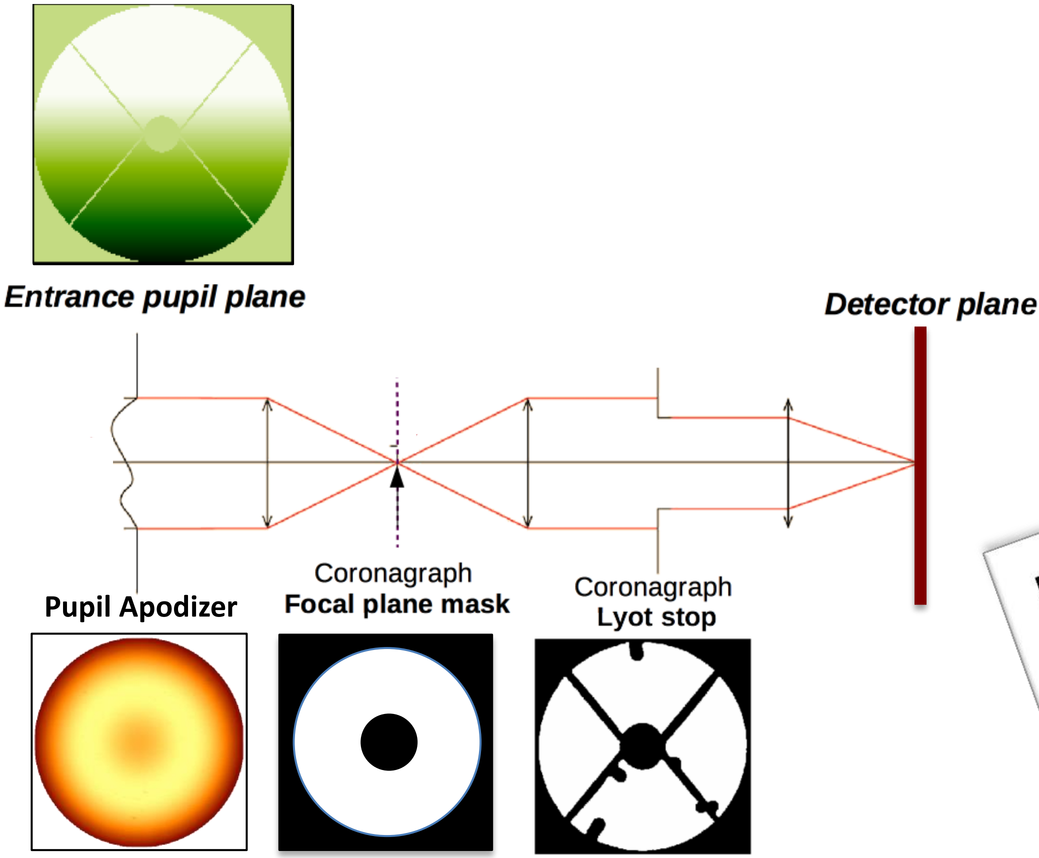
The contrast killers #1

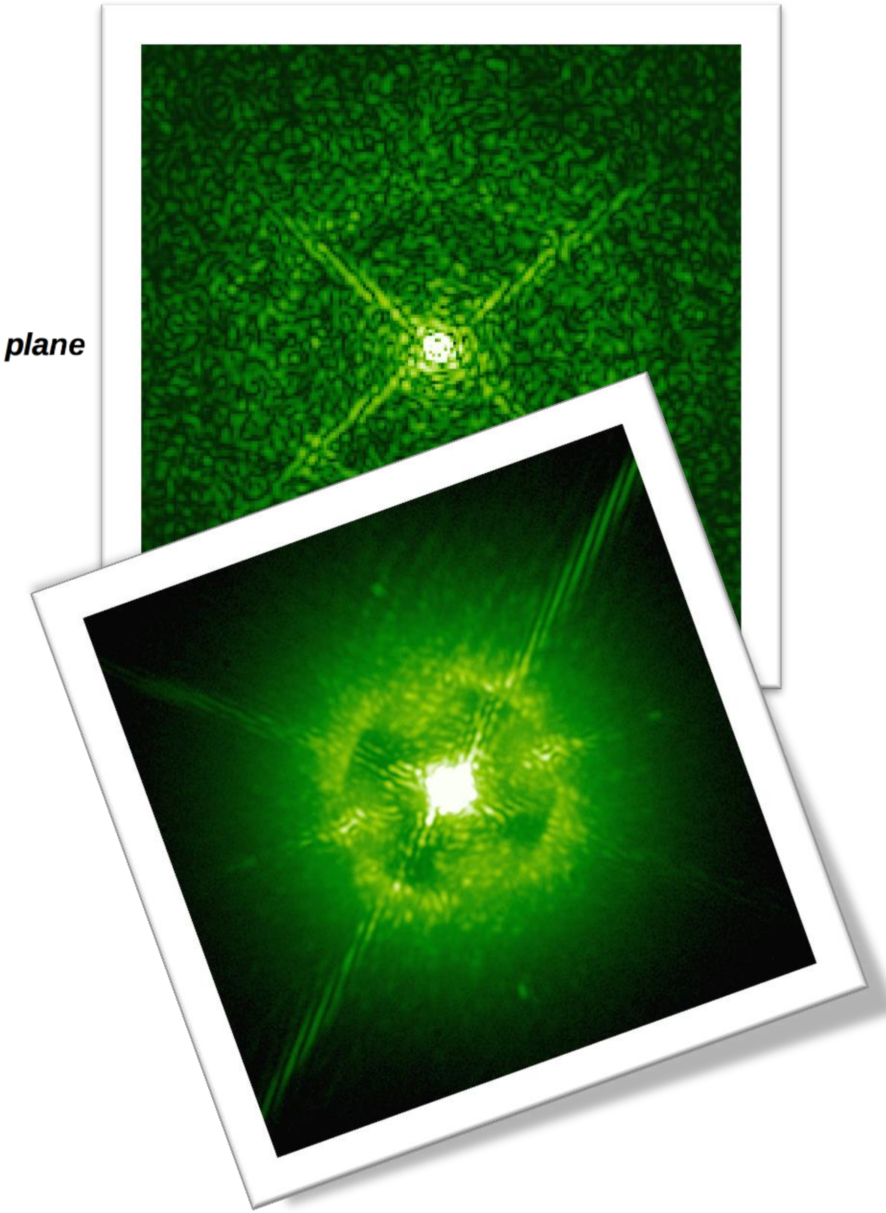


Responsible for the “**jitter**”



Diffraction by the spiders





Low order residuals (Tip-tilt):

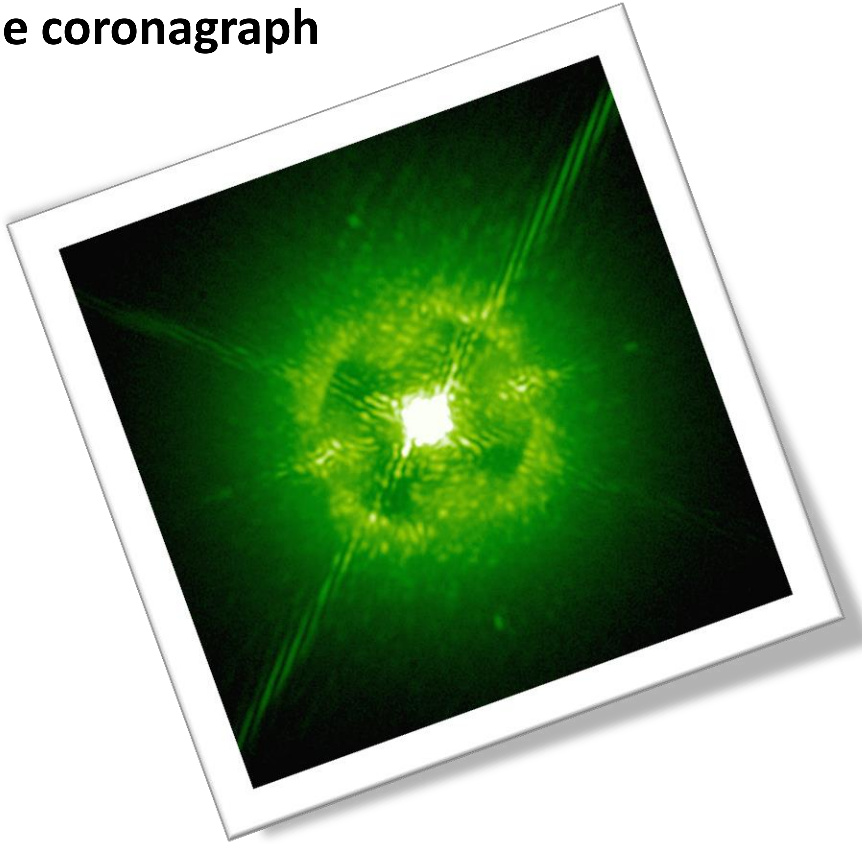
Lyot stop not ‘centered’ anymore

Diffraction by the spiders

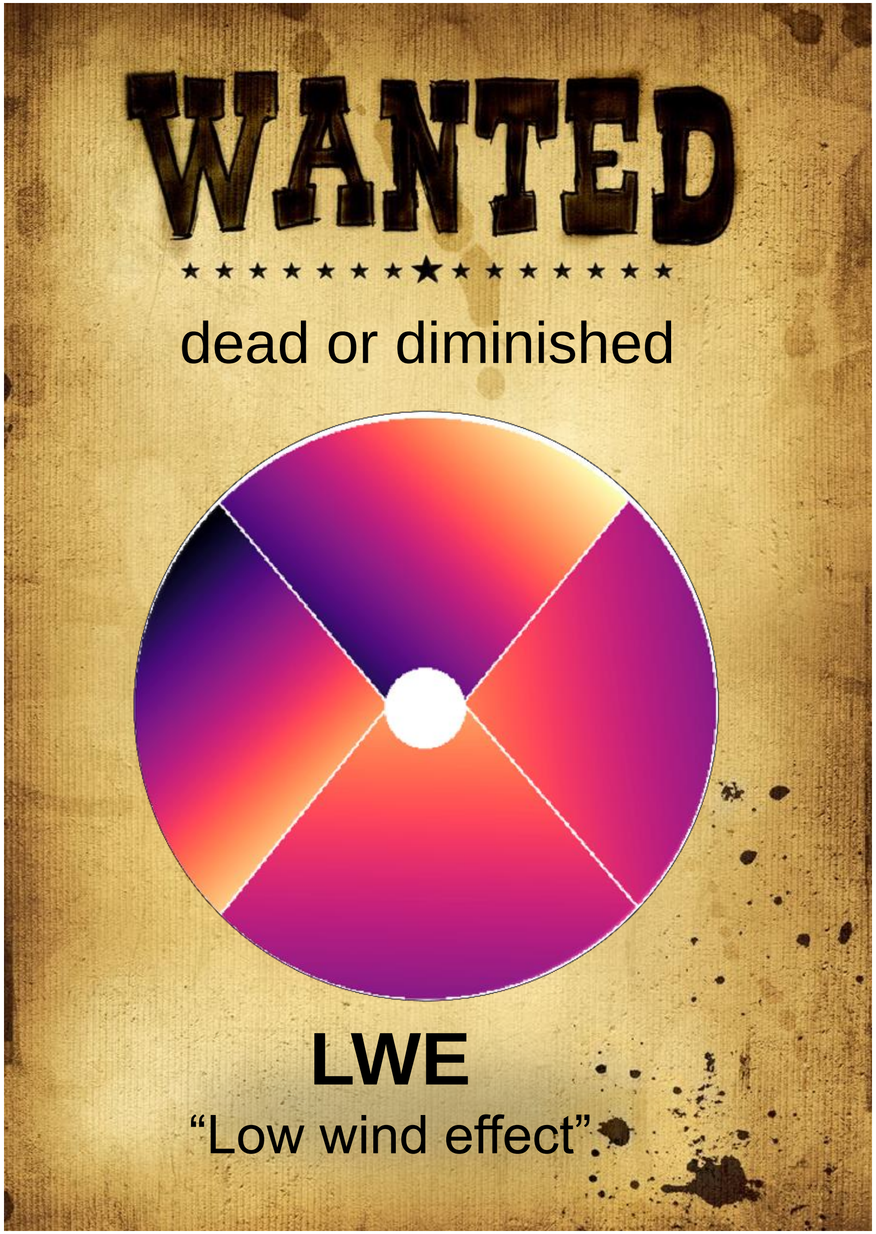
<u>Can be caused by:</u>

- Atmospheric residuals: ~ 30 mas
- Vibrations: ~ 10 mas
- Atmospheric dispersion residuals: ~ 10 mas

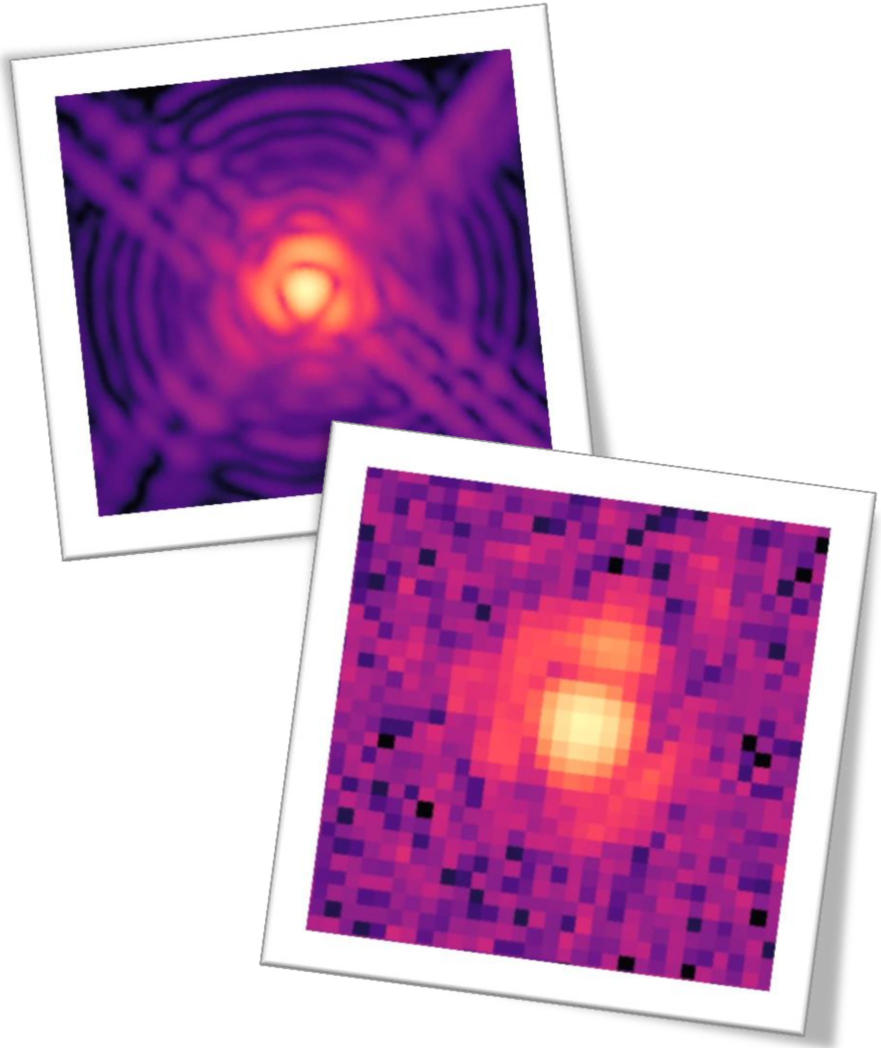
→ Not a limitation if using a **pupil plane coronagraph** (e.g. APP, pupil shaped…)



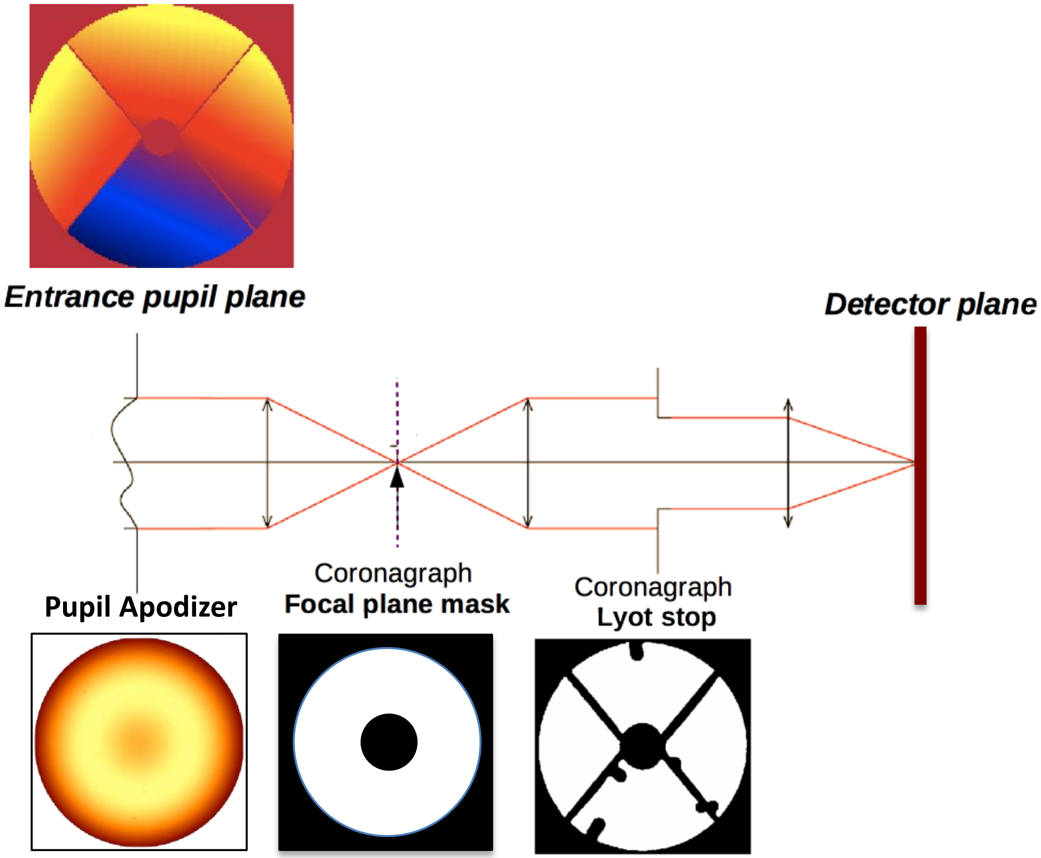
The contrast killers #2

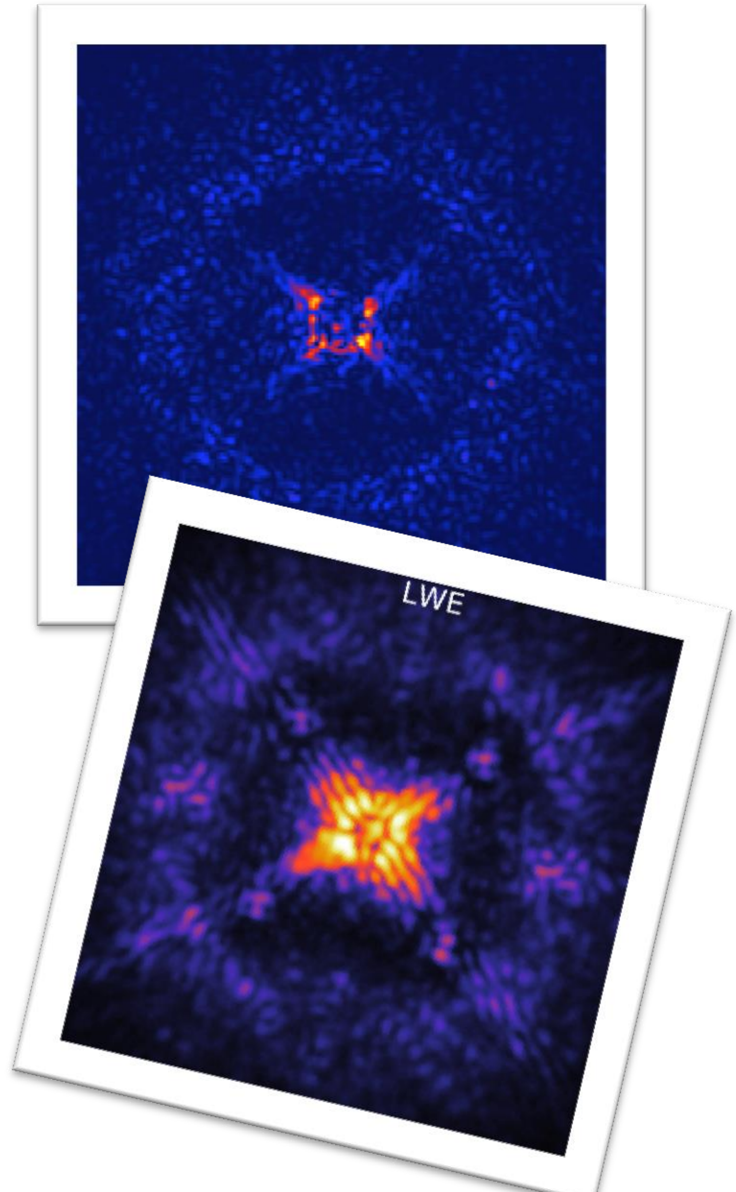


Responsible for the
"**Mickey Mouse effect**"



The low wind effect





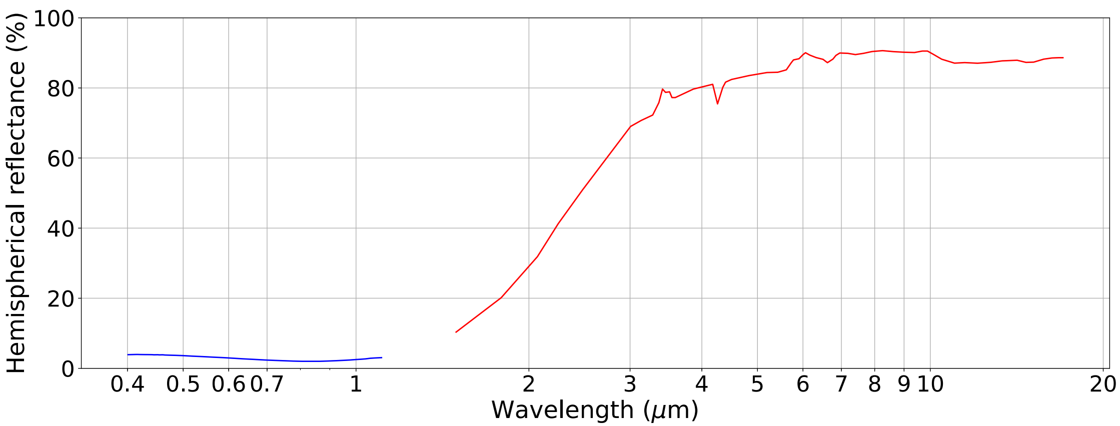
Low wind effect:

Leakage around the focal plane mask

The low wind effect

Mitigation:

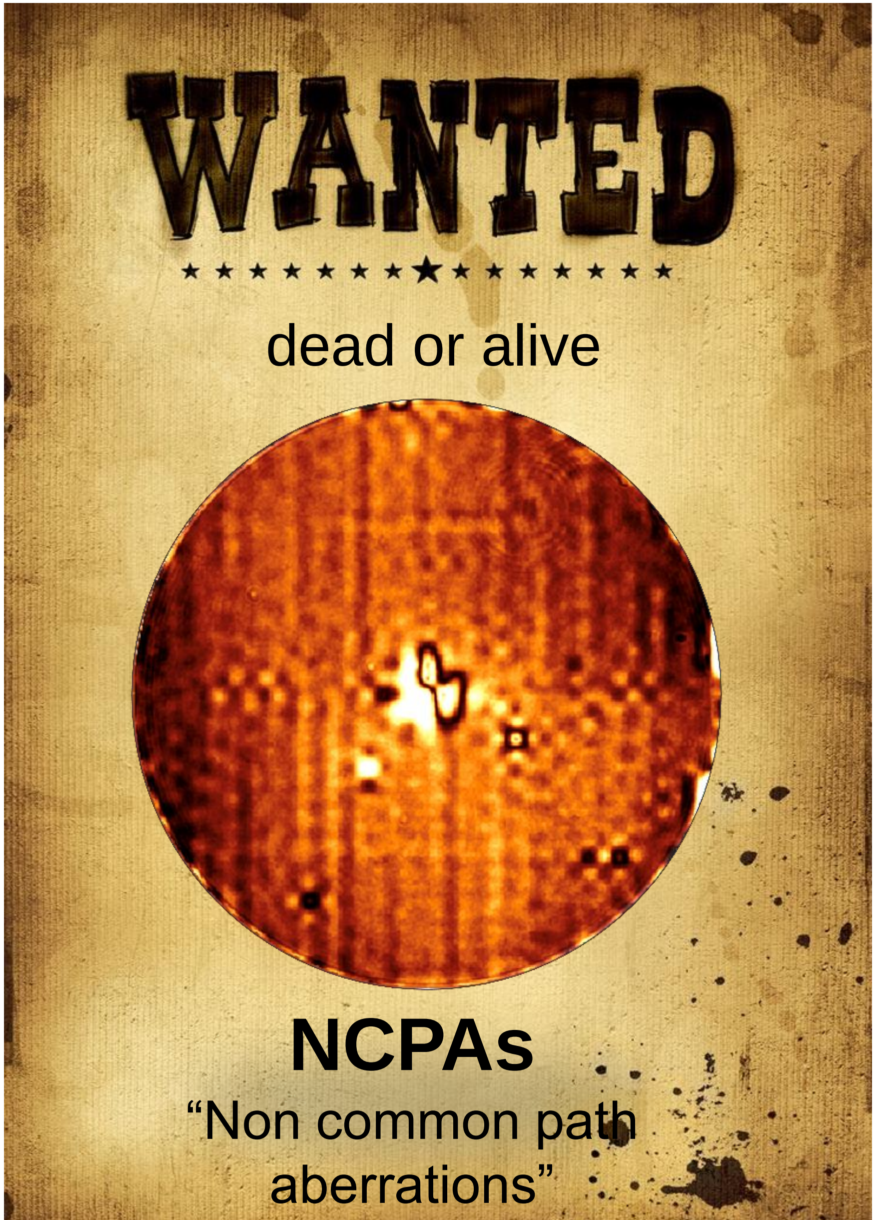
- **Software solutions**: but instrument-dependent
- **Active solutions** (spiders heating, ventilation): too invasive
- **Passive solution** retained: low emissivity coating



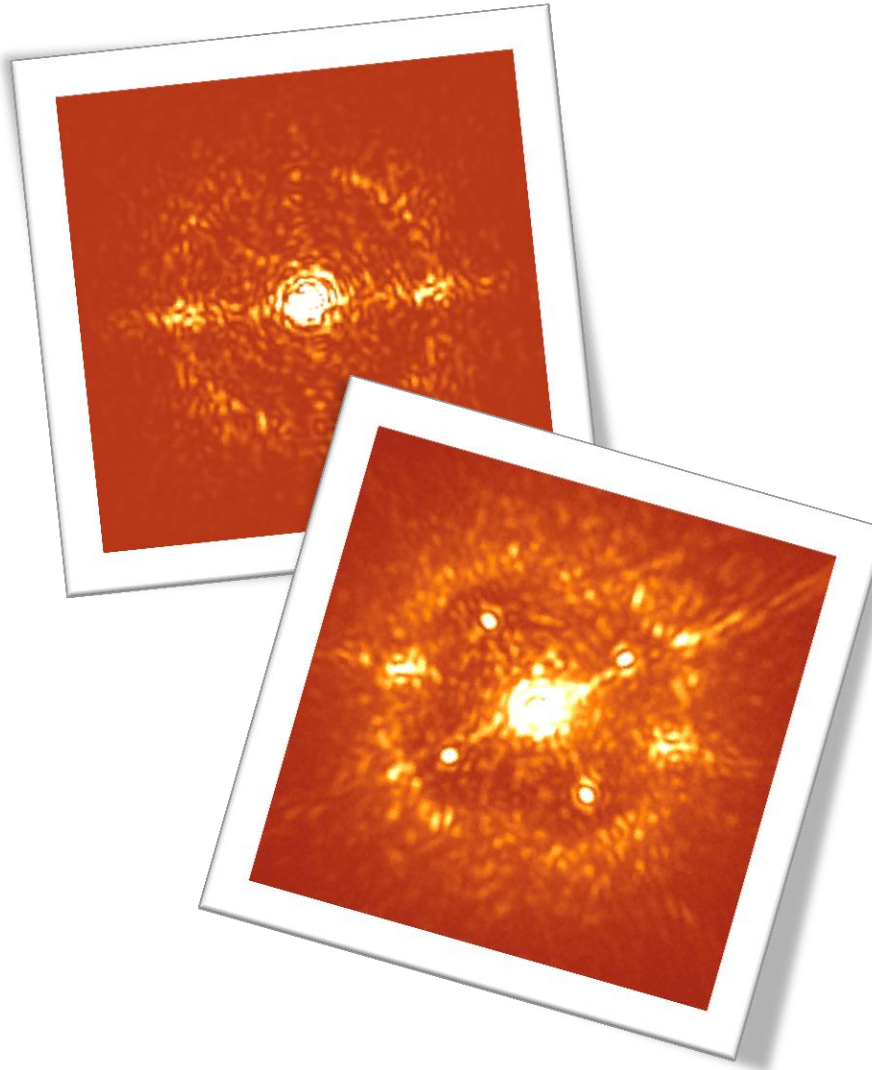
Aktar Nanoblack ®

On VLT/UT4 (SPHERE):
Occurrence from 18% to 3% !

The contrast killers #3



Responsible for the
“**quasi-statics speckles**”

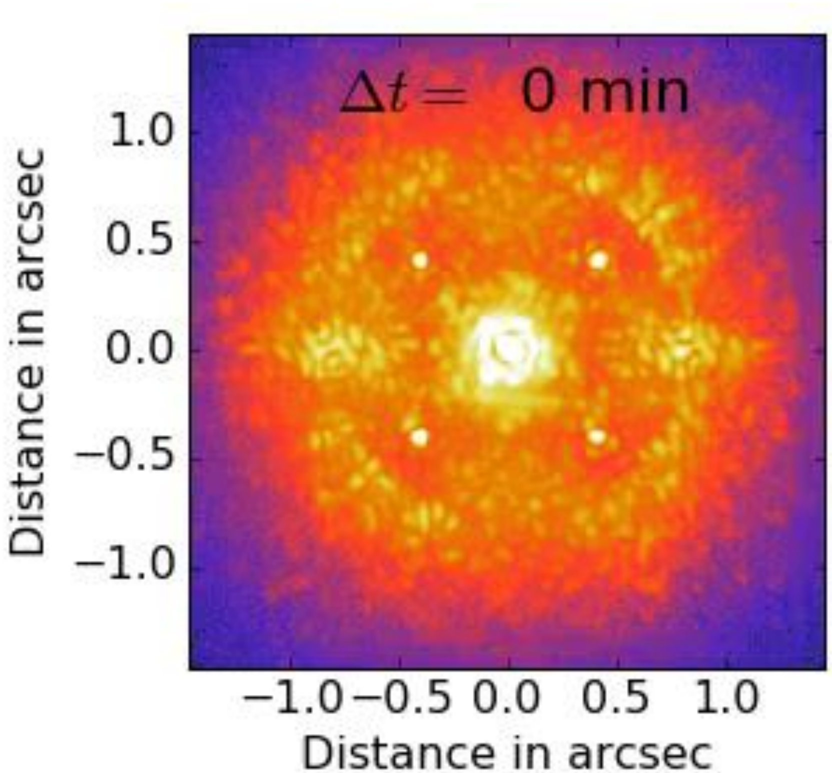


The NCPAs

Quasi-statics speckles are the problem:

-**Too slow:** Cannot be averaged in a halo

-**Too fast:** Cannot be calibrated



Due to optical defaults:

- Temperature changes,
- Pressure changes,
- Gravitational bent,
- Internal turbulence,
- …

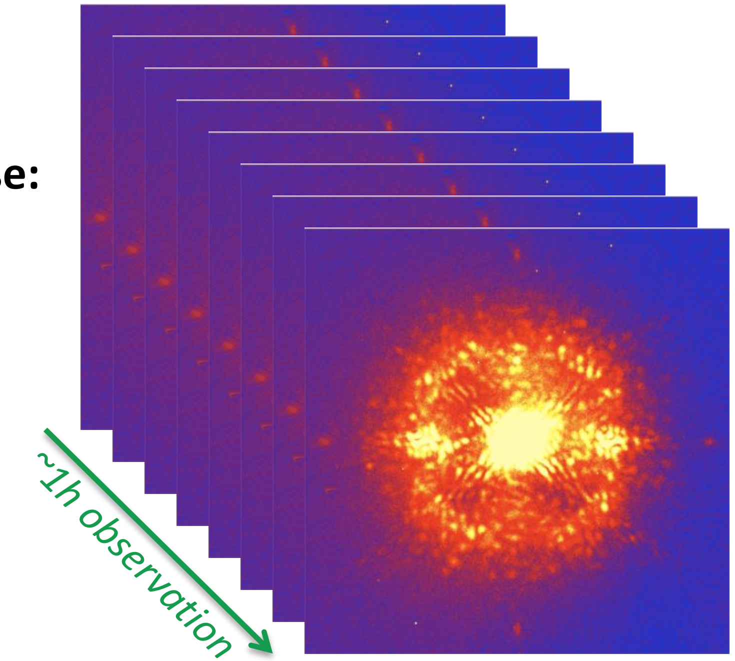
The Quasi-static speckles

Post-processing techniques are trying to get rid of those:

Basic idea:

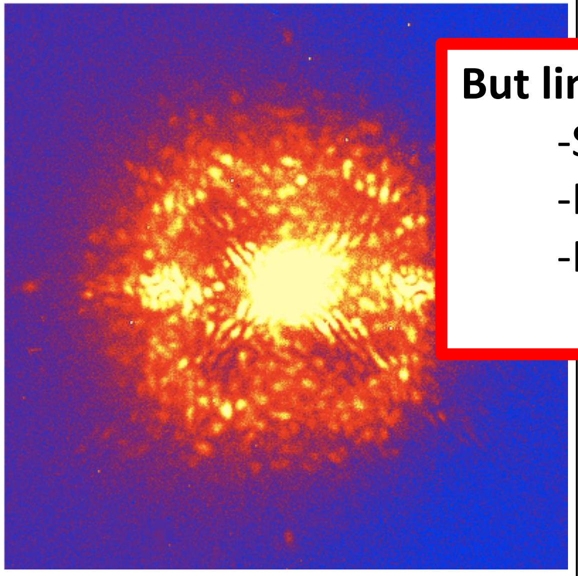
Find a **different** behavior between the speckles and the astrophysical signals.

→ **Exploit this diversity to recover the signal**

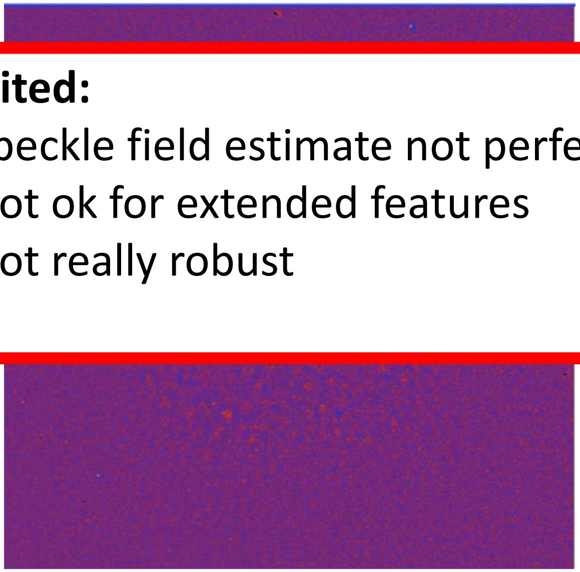


Today, all are based on **differential imaging**:

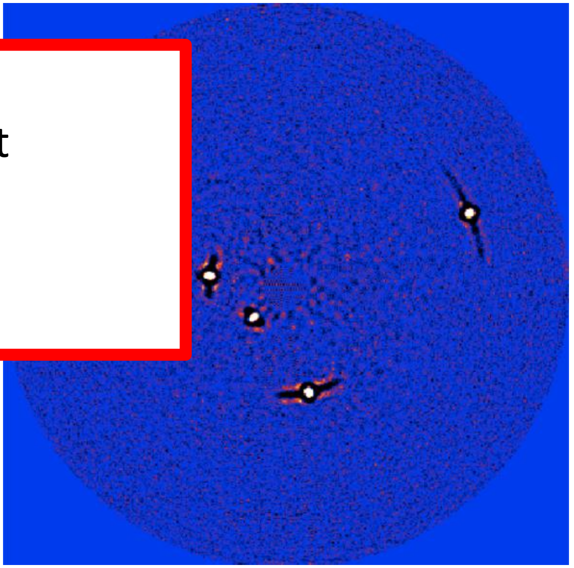
1. **Estimate** the star image



2. **Subtract** it to the image



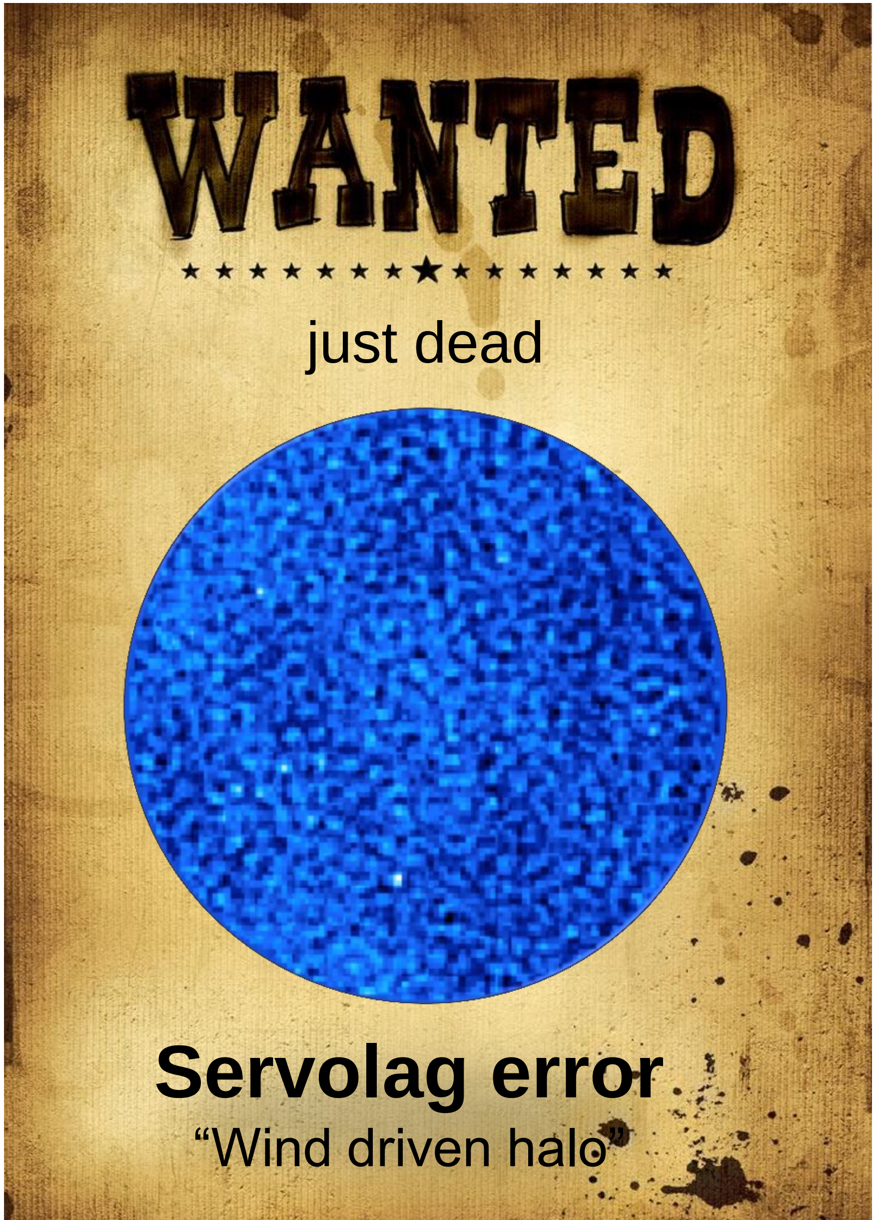
3. **Combine** all the images



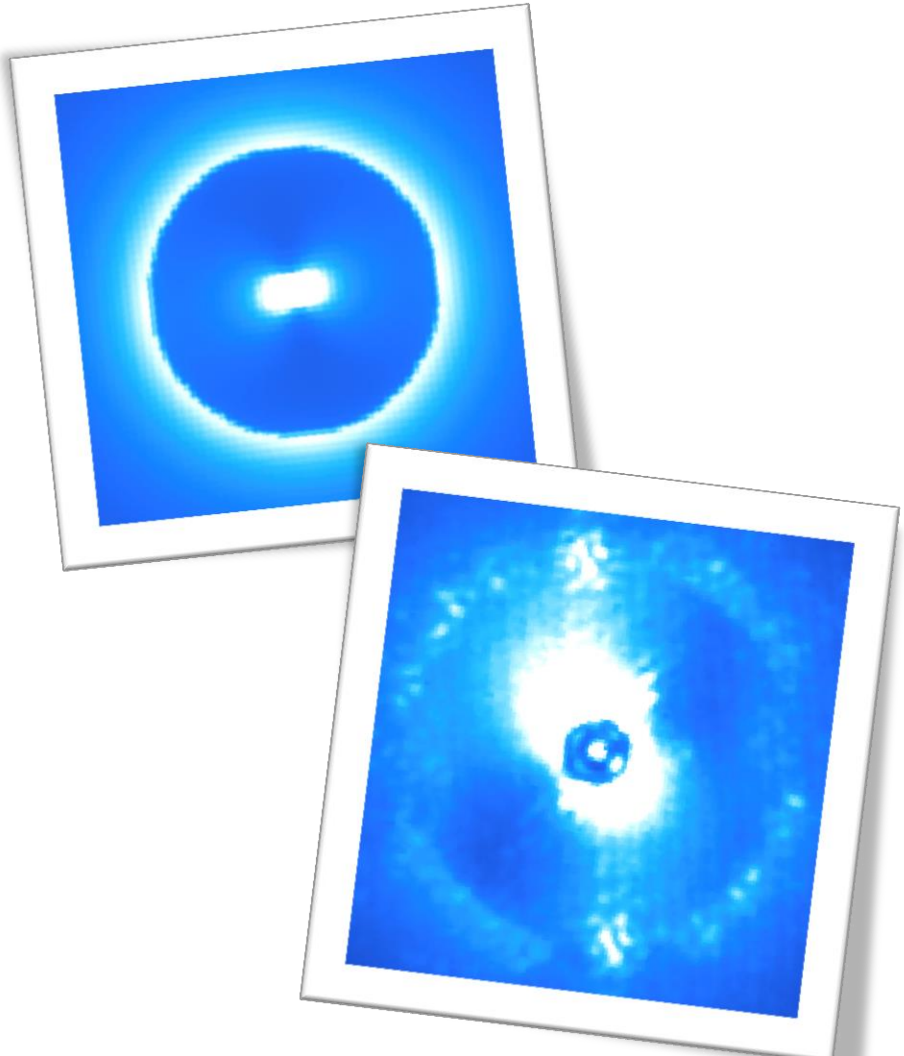
But limited:

- -Speckle field estimate not perfect
- -Not ok for extended features
- -Not really robust

The contrast killers #4



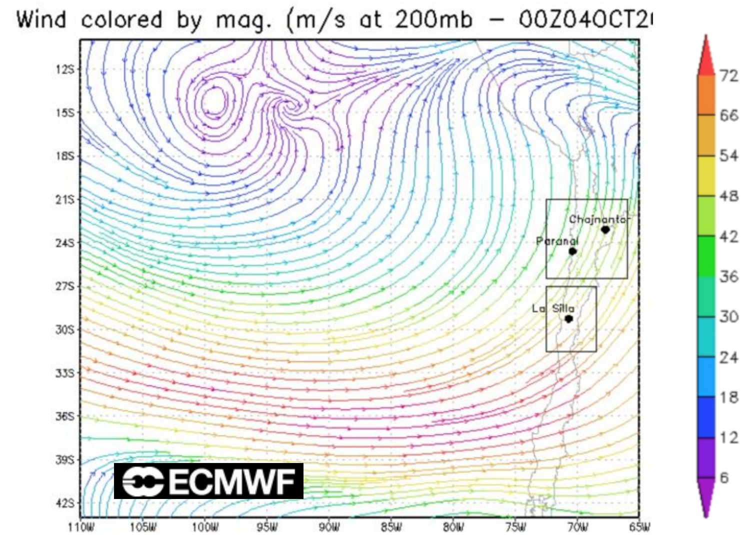
Responsible for the
“~~butterfly effect~~” **“Wind drive halo”**



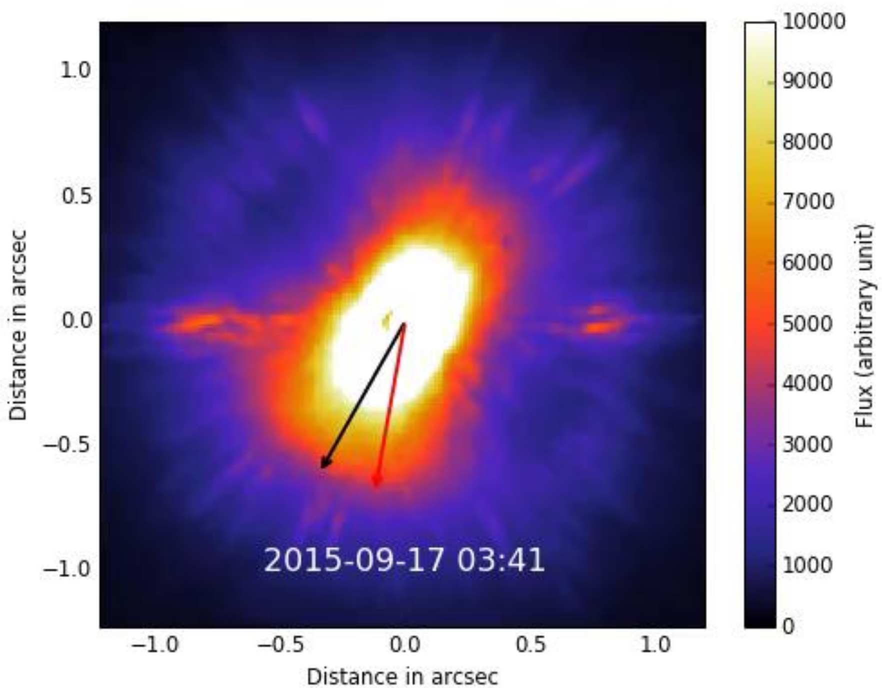
The wind driven halo

AO Servolag / temporal bandwith error:
AO lag vs turbulence speed

Jet stream layer at 12km:
Wind speed from 20 to 50m/s !



jetstream wind forecast

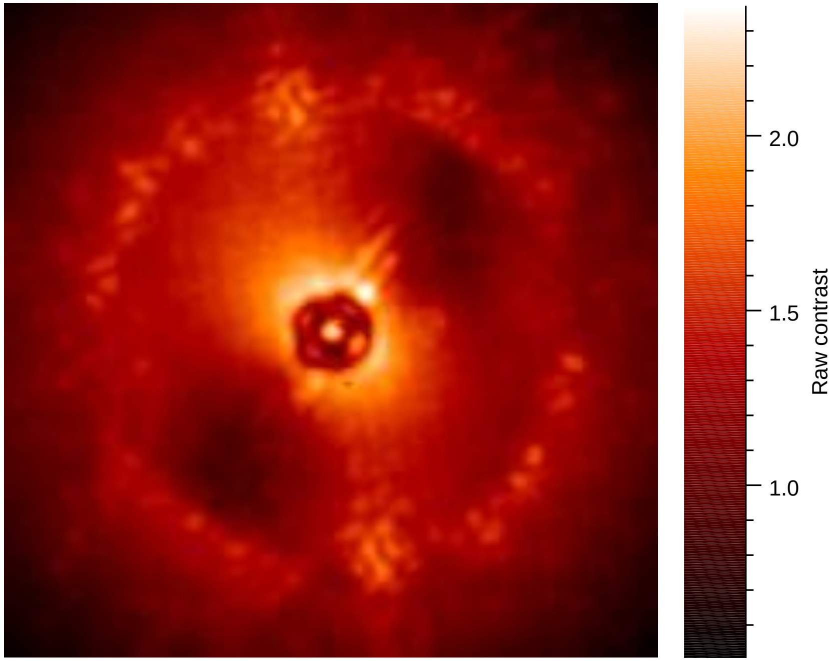


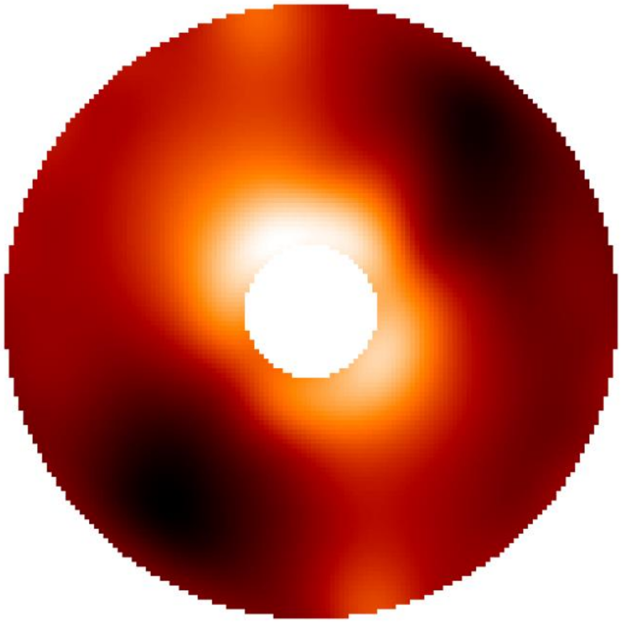
Movie from SHARDDS
(SPHERE-IRDIS – Broadband H):
Red arrow: ground layer
Black arrow: jet stream layer

See also Madurowicz et al., SPIE 2018 (GPIES)

Analysis of the WDH

1- Isolate the WDH contribution



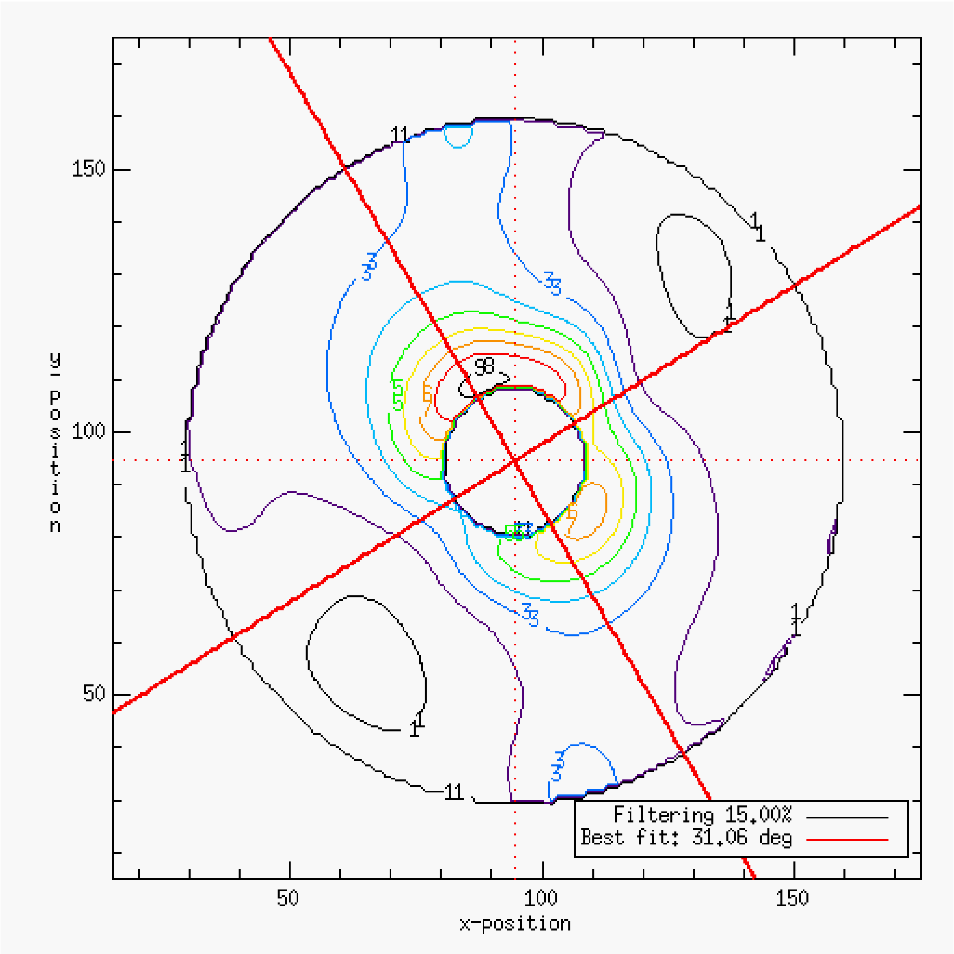


Coming soon: analysis of the SHINE survey
correlation w/ profiling

Analysis of the WDH

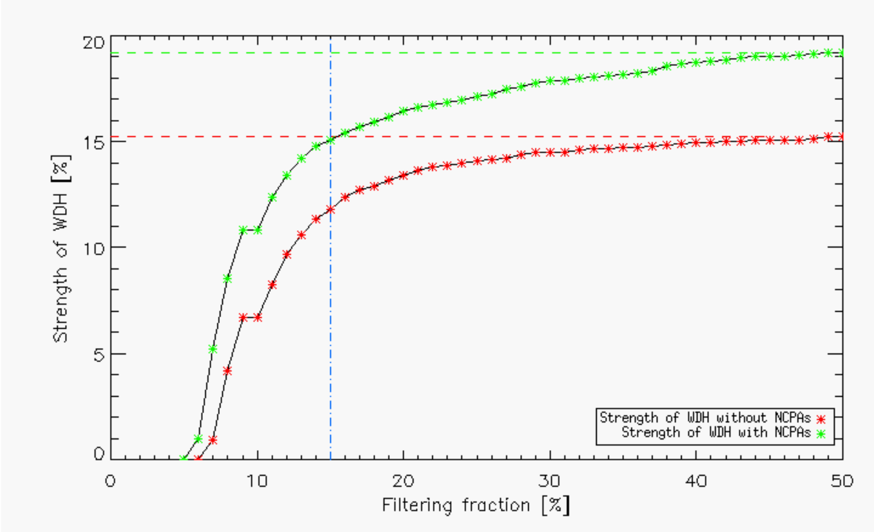
1- Isolate the WDH contribution

2- Derive its direction (absolute)



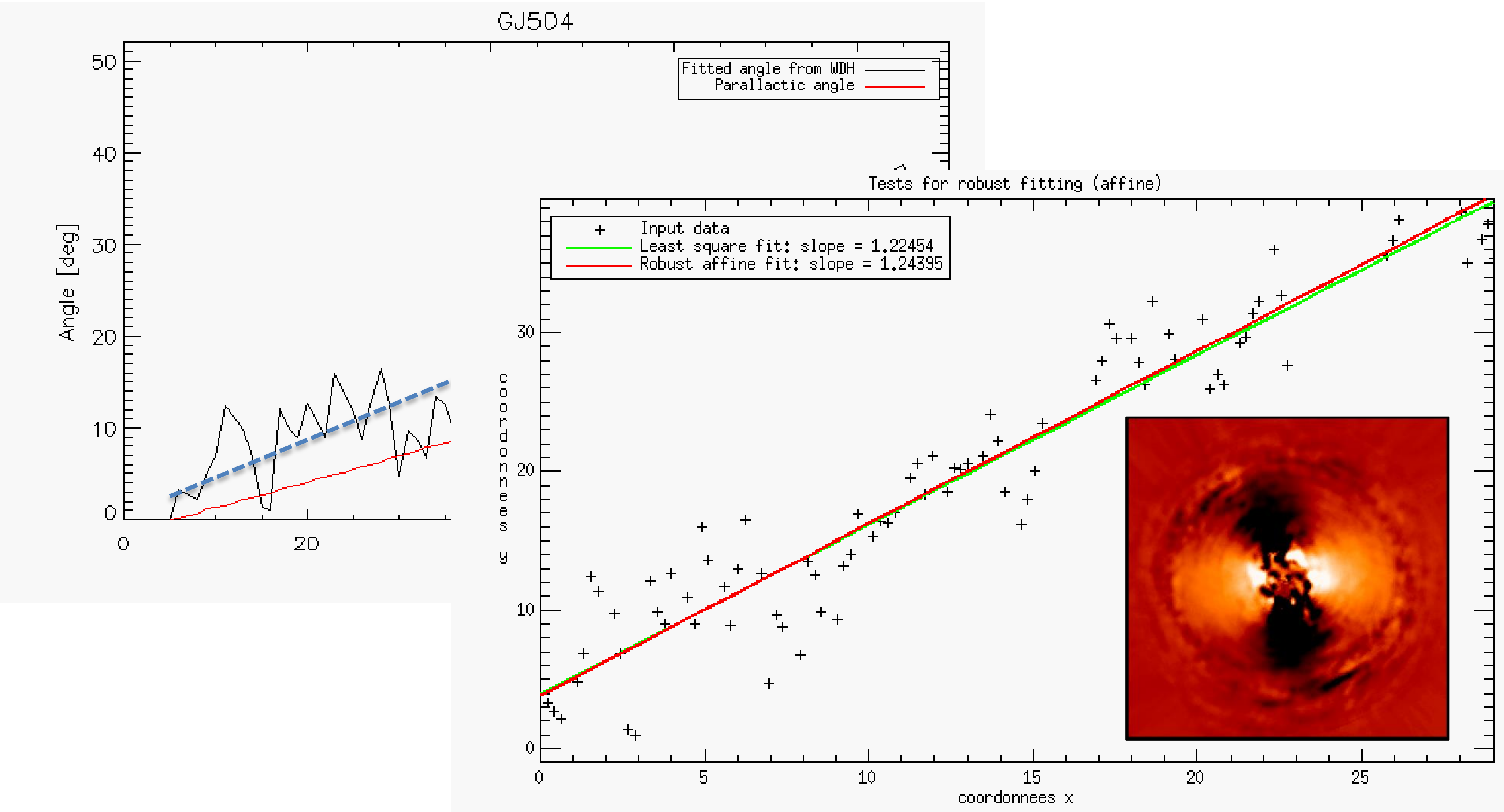
3- Compute its strength (relative)

$$S_{WDH} = \frac{\int(\bar{I}_{>\tau}(x,y)\times mask)}{\int(I(x,y)\times mask)}/100.$$



Coming soon: analysis of the SHINE survey correlation w/ profiling

Temporal behavior

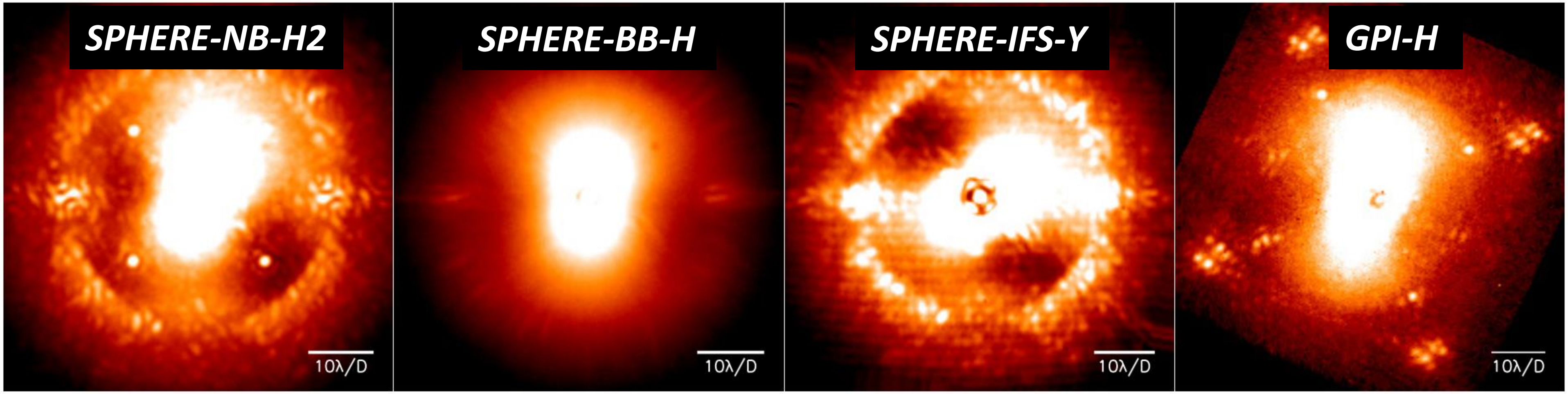


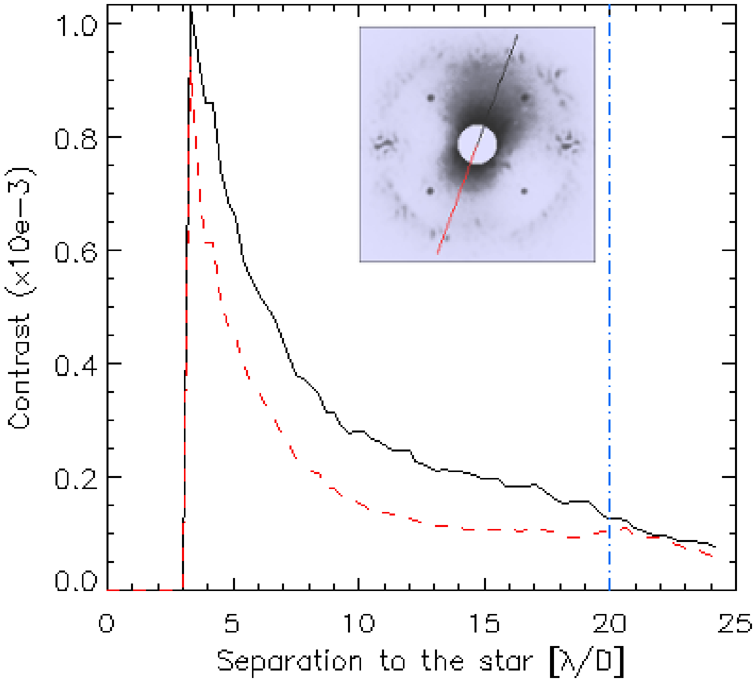
The temporal variation doesn't match exactly

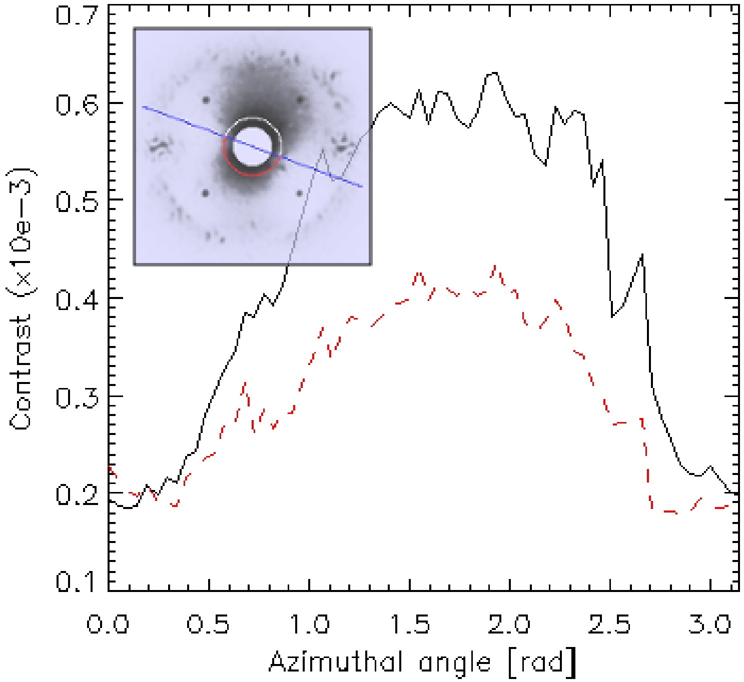
--> Remains in ADI post-processing

Coming soon: spectral behavior for SDI

Description of the asymmetry







Origin of the asymmetry

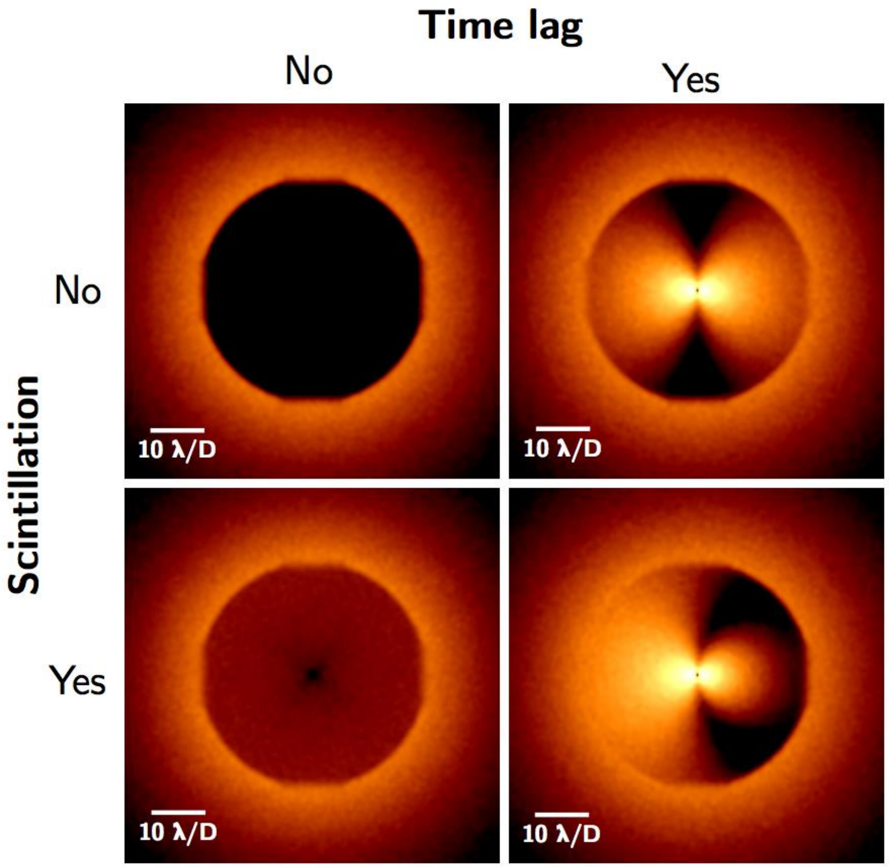
Interferences between correlated:

-**Amplitude errors** -> provoked by **scintillation** from upper layer

-**Delayed phase errors** -> provoked by **AO-lag** (servolag error)

Important messages:

- Any coronagraph reveals it
- A few scintillation is enough



SPHERE-like simulations using HCIpy
(https://github.com/ehpor/hcipy)

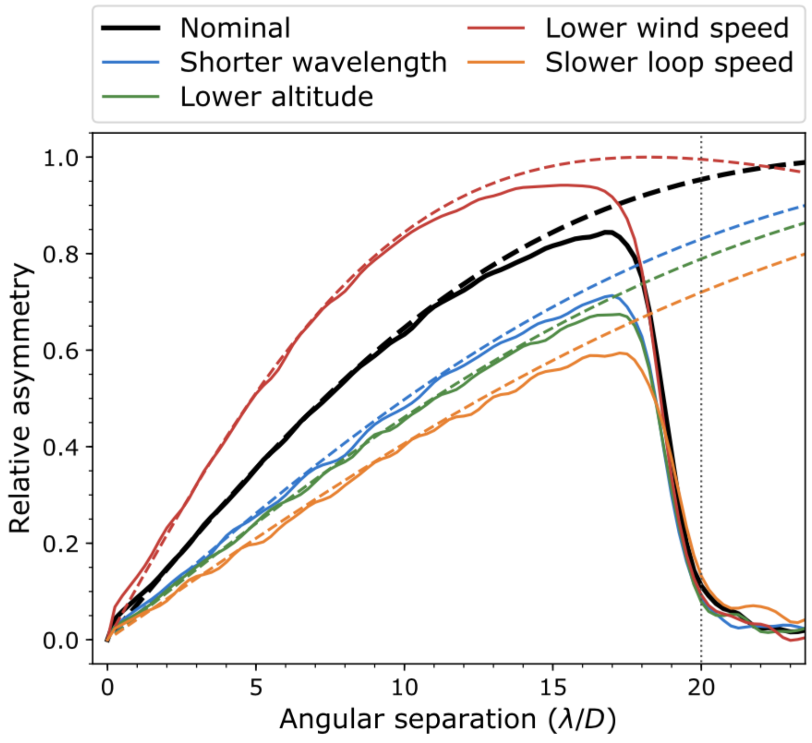
Consequences on the images

Asymmetry factor: $$F_{asymmetry} \doteq \frac{I_+ - I_-}{I_+ + I_-}$$

Taylor expansion:
(scintillation ignored) $$F_{asymmetry} = \frac{zf\lambda}{v_{wind}\,\Delta t} + O\left(\left(\frac{zf\lambda}{v_{wind}\,\Delta t}\right)^2\right)$$

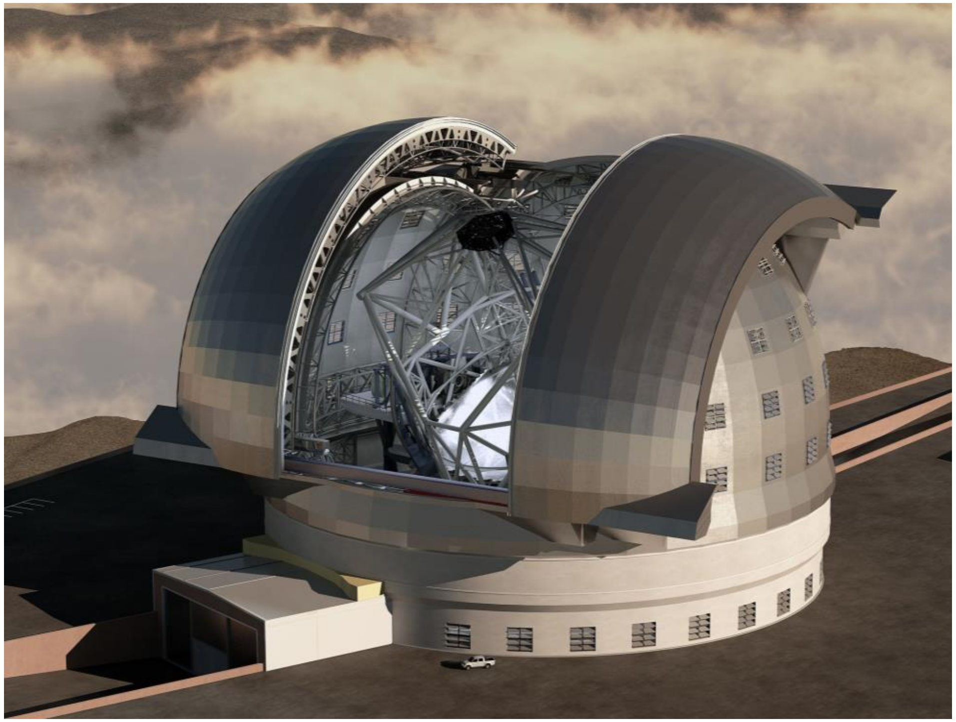
Asymmetry increases with:

- The angular separation, **f**
- Larger wavelength, **λ**
- Higher atmospheric layer, **z**
- Slower wind speed, $\mathbf{v_{wind}}$
- Small absolute AO delay, **Δt**



Solution: Move to Mauna Kea
Solution: Post-processing, predictive control…

What about ELT instruments …



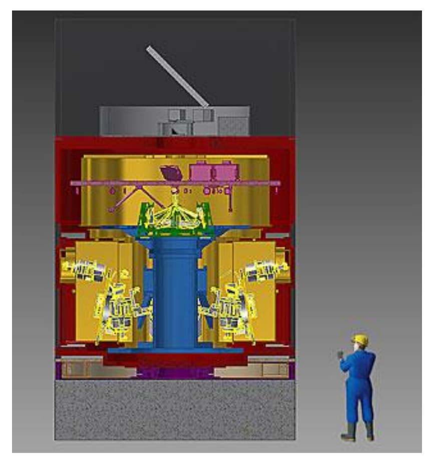
METIS

Mid-infrared
E-ELT Imager and
Spectrograph

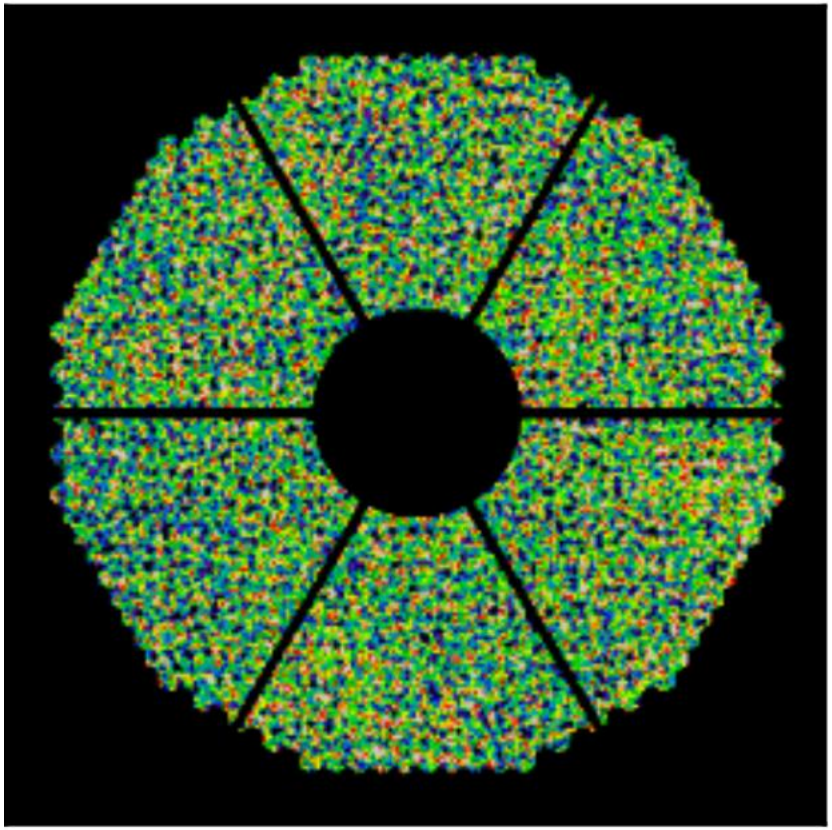
MICADO

Three instruments foreseen

→ They all have a high contrast mode !

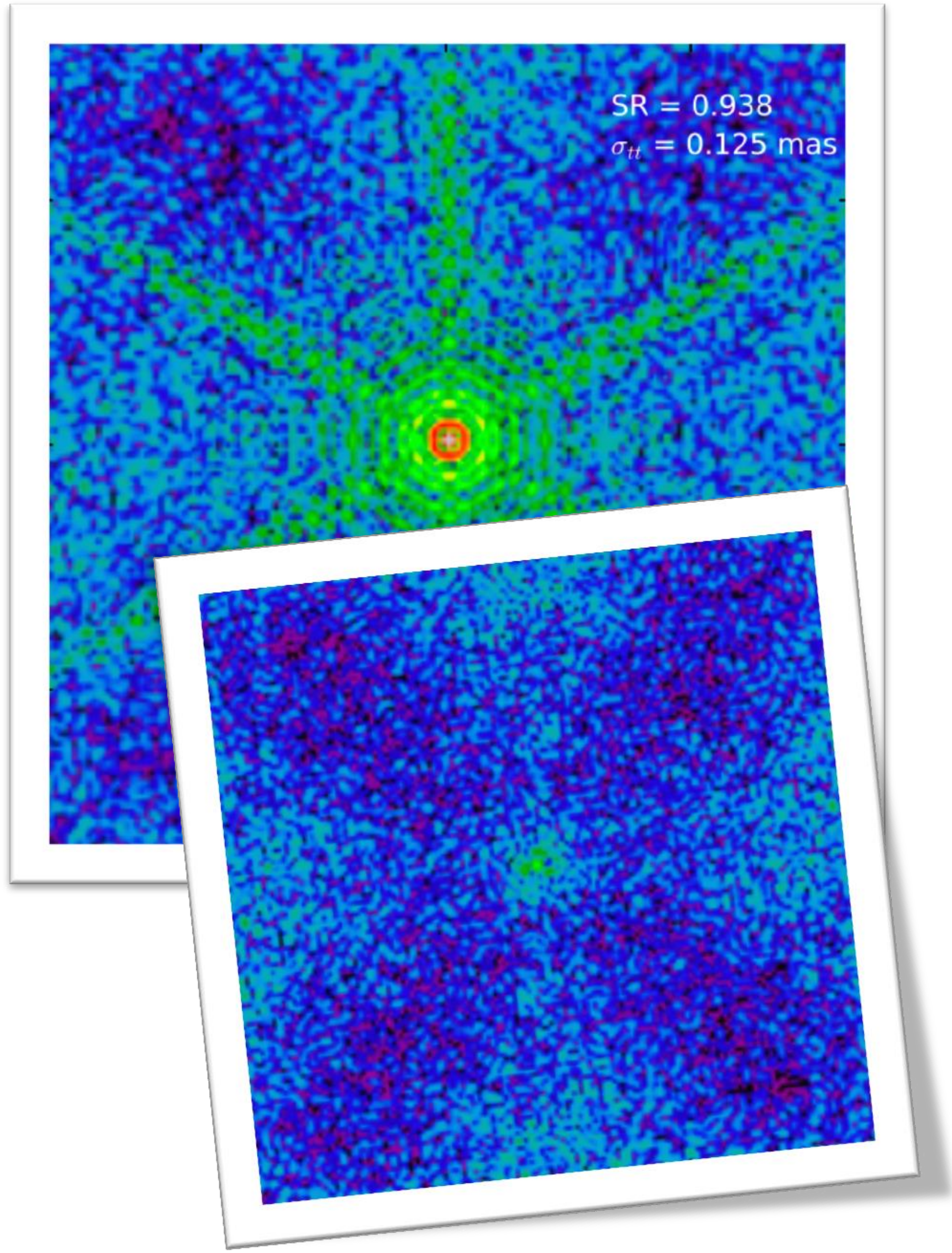


What about ELT instruments …



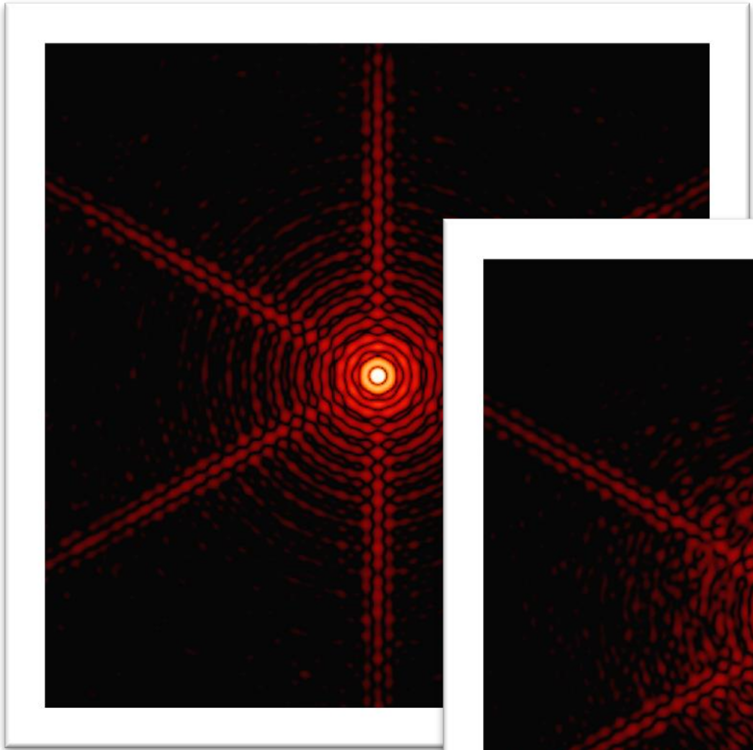
Simulations from Silvia and Markus

METIS analytical simulations

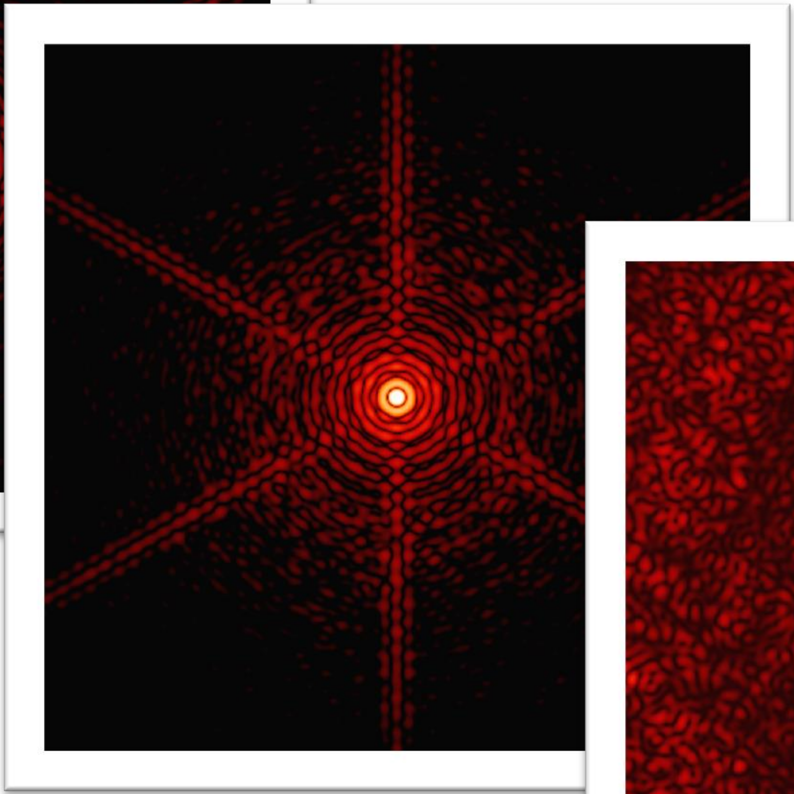


What about ELT instruments ...

METIS end-to-end simulations

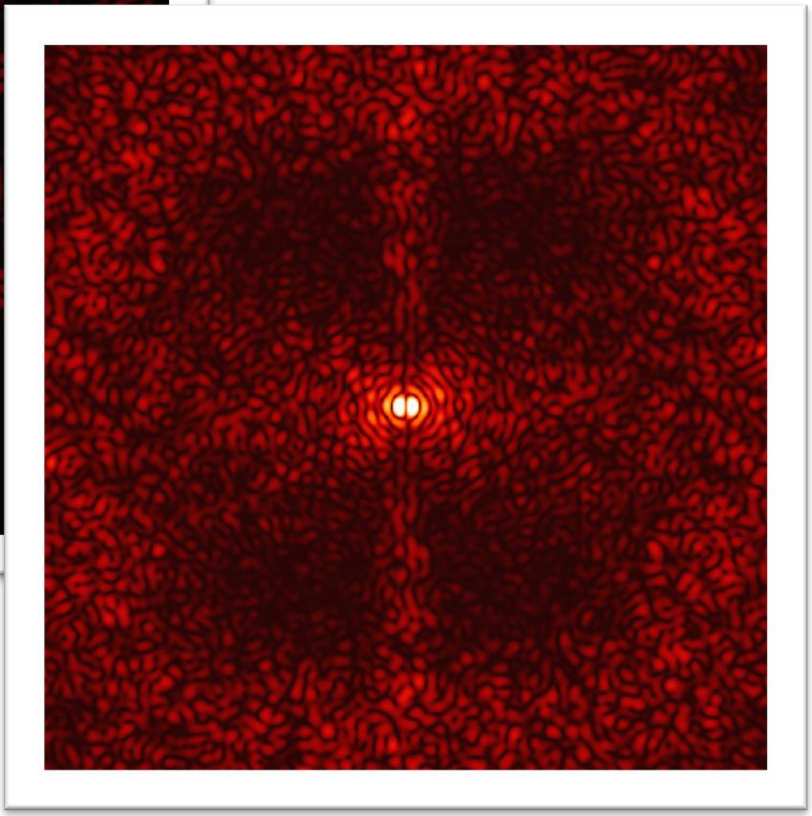


Diffraction only



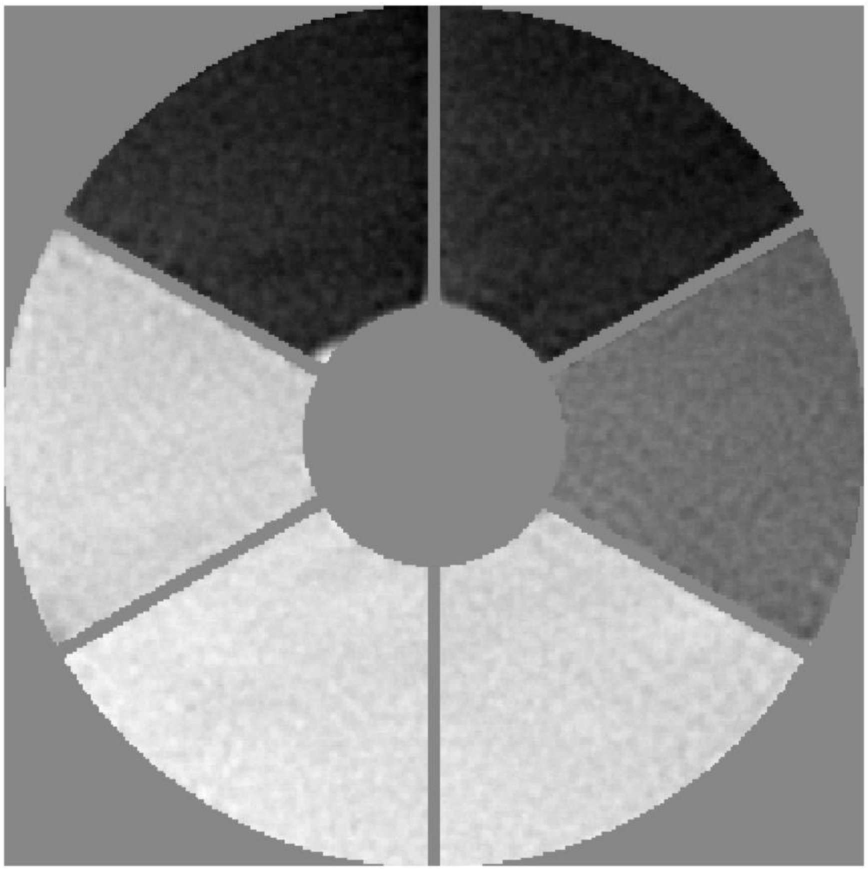
Diffraction + AO residuals

Coronagraphic image...



What about ELT instruments …

The infamous "**Island effect**" due to pupil fragmentation:
This is a different origin from low wind effect or atmospheric piston !
But same effect on the PSF…



METIS end-to-end simulations

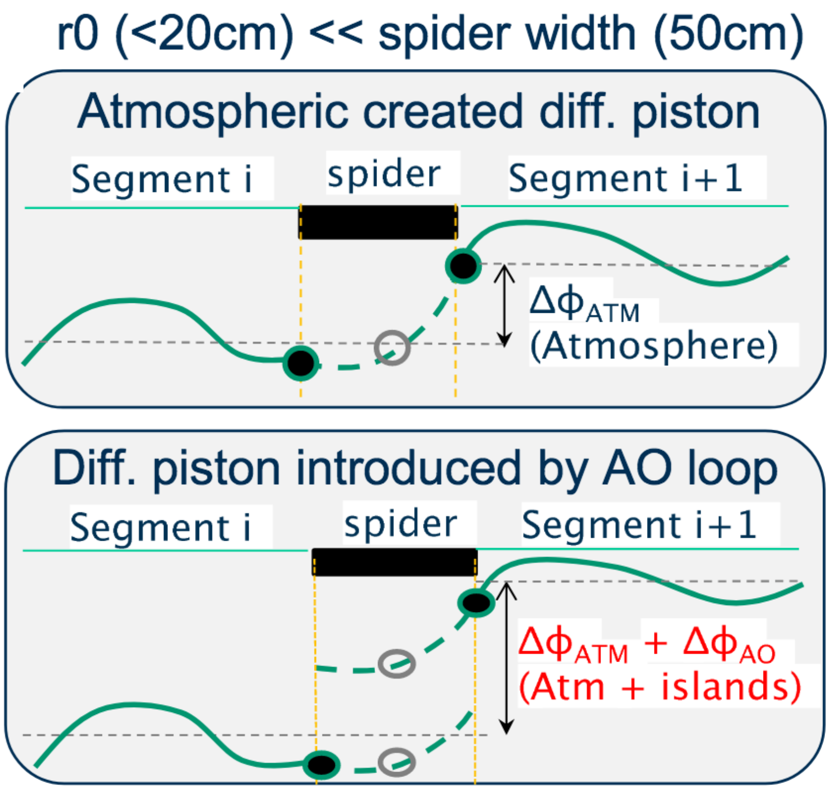


Illustration N. Schwarz (UK-ATC)

Summary and conclusions

- Within the SPHERE images, you can **spot** most error terms
  See Dohlen et al. SPIE 2016
- **Four** of them are definitely killing the contrast
  See Vigan et al. SPIE 2018, Milli et al. SPIE 2018, Cantalloube et al. in prep.
- Among which the **asymmetry** of the wind driven halo,
  See Cantalloube et al. 2018
- For **ELT**, every instrument has an HCI mode
  Let’s have fun !